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Professor J. McKeen Cattell, M.A., Ph.D.

AND

F. E. Beddard, M.A., F.R.S.

EARTH SCULPTURE

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OR

THE ORIGIN OF LAND-FORMS

BY

JAMES GEIKIE, LL.D., D.C.L., F.R.S., ETC.

MURCHISON PROFESSOR OF GEOLOGY AND MINERALOGY
IN THE UNIVERSITY OF EDINBURGH; FORMERLY OF H.M. GEOLOGICAL SURVEY
AUTHOR OF "THE GREAT ICE AGE," "PREHISTORIC EUROPE," ETC.

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PREFACE

ALTHOUGH much has been written, especially of late years, on the origin of surface-features, yet there is no English work to which readers not skilled in geology can turn for some general account of the whole subject. It is true that all geological text-books, and many manuals of geography, devote some space to its discussion, while not a few excellent treatises deal at large with one or more of its subdivisions. Geological literature is also by no means poor in admirable popular monographs descriptive of the geology and geography of particular regions, in which the origin of their surface-features is more or less fully explained. But for those who may be desirous of acquiring some broad knowledge of the results arrived at by geologists as to the development of land-forms generally, no introductory treatise is available. Possibly, therefore, the present attempt to supply a deficiency may not be wholly unacceptable.

In a work addressed more particularly to non-specialists, technical terminology should be employed as sparingly as possible, and I have consequently made scant use of those neologisms in which, unfortunately,

the recent literature of the subject too much abounds. Technical words and expressions cannot, however, be entirely dispensed with, but those which my readers will encounter have, as a rule, been long current, and few are likely to be unfamiliar.

The materials used in the preparation of this book are for the most part from the common stock of geological knowledge, and it has not been thought necessary, therefore, to burden the pages with references. Those who would pursue the subject further must consult the larger text-books of geology in English, French, and German, which usually indicate the more notable sources of information. The following works will also be found very helpful as guides and instructors :—

Sir A. C. Ramsay's *Physical Geology and Geography of Great Britain.*

Prof. A. H. Green's *Physical Geology* (chap. xiii.).

Sir A. Geikie's *Scenery and Geology of Scotland.*

Prof. E. Hull's *Physical Geology and Geography of Ireland.*

Sir J. Lubbock's *Scenery of Switzerland and the Causes to which it is Due.*

Dr. E. Fraas's *Scenerie der Alpen.*

Major J. W. Powell's *Canyons of the Colorado.*

MM. De la Noë and Emm. de Margerie, *Les Formes du Terrain*—an admirable and well illustrated work, descriptive of the geological origin of land-forms.

Prof. A. Penck's *Morphologie der Erdoberfläche*—a

masterly review and classification of the surface-features of the earth, with a full discussion of their origin. This treatise is particularly rich in references to the literature; the whole history of geological opinion on the subject of which it treats may therefore be gathered from its pages.

Prof. A. de Lapparent's *Leçons de Géographie Physique*—a most instructive and comprehensive outline of geo-morphology. The second half of the work deals more particularly with geographical evolution, the special treatment of which does not come within the limits of my essay. This interesting subject has of late years been studied with great assiduity, especially by Prof. W. M. Davis and others in North America.

The maps and sections, and the monographs, memoirs, and reports of our own and other national geological surveys are storehouses of information and instruction in physiographical geology. Some of these works that deal more especially with denudation and the relation of surface-features to geological structure have indeed become classical. Amongst these are Ramsay's notable paper, "On the Denudation of South Wales and the Adjacent Counties of England" (*Memoirs Geological Survey of England*, vol. i., 1846); Heim's *Mechanismus der Gebirgsbildung*, etc. (which, although an independent work, was yet commenced under the auspices of the Swiss Geological Commission); Dutton's "Tertiary History of the Grand Cañon District" (*Monograph II. of U. S. Geological Survey*).

For the use of several illustrations (Figs. 8, 25, 26, 75, 78) from Major Powell's *Canyons of the Colorado*, I am indebted to his publishers, Messrs. Flood & Vincent. I am under similar obligations to the Council of the Geological Society for a section (Fig. 34) borrowed from my brother's paper on the North-west Highlands; to Mr. Stanford for reproductions of illustrations (Figs. 77, 83, 87, 88) from my *Outlines of Geology;* to Herr Tempsky, Vienna, for Figs. 41, 45, 56, from Kirchhoff's *Länderkunde des Erdteils Europa;* and to my friend, Mr. W. E. Carnegie Dickson, for the photographs reproduced on Plates I. and II.

EDINBURGH, July 1, 1898.

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EARTH SCULPTURE

CHAPTER I

INTRODUCTORY

EARLY VIEWS AS TO ORIGIN OF SURFACE-FEATURES—ROCKS AND ROCK-STRUCTURES—ARCHITECTURE OF THE EARTH'S CRUST —GENERAL EVIDENCE OF ROCK-REMOVAL.

WHEN geologists began to inquire into the origin of surface-features, they were at first led to believe that the more striking and prominent of these had come into existence under the operation of forces which had long ago ceased to affect the earth's crust to any marked extent. It is not hard to understand how this conception arose. The earlier observers could not fail to be impressed by the evidence of former crustal disturbances which almost everywhere stared them in the face. Here they saw mountains built up of strangely fractured, contorted, and jumbled rock-masses; there, again, they encountered the relics of vast volcanic eruptions in regions now practically free from earth-throes of any kind. In one place ancient land-surfaces were seen intercalated at inter-

vals among great successions of marine strata; in other places, limestones, evidently of oceanic origin, were found entering into the framework of lofty mountains far removed from any sea. It was these and similar striking contrasts between the present and the past which doubtless induced the belief that the earth's crust, after having passed through many revolutions more or less catastrophic in character, had at last become approximately stable—the occasional earthquakes and volcanic disturbances of recent times being looked upon as only the final manifestations of those forces which in earlier ages had been mainly instrumental in producing the varied configuration of the land. Mountains and valleys belonged to earth's *Sturm und Drang* period. That wild time had passed away, and now old age, with its lethargy and repose, had supervened. The tumultuous accumulations of stony clay, blocks and boulders, gravel and sand that overspread extensive areas in temperate latitudes were believed to be the relics of the last great catastrophe which had affected the earth's surface. Some notable disturbance of the crust, it was thought, had caused the waters of northern seas to rush in devastating waves across the land. When these diluvial waters finally retired, then the modern era began—an era characterised by the more equable operation of nature's forces.

But with increased knowledge these views gradually became modified. Eventually, it was recognised that no hard-and-fast line separates past and present.

The belief in world-wide, or nearly world-wide, catastrophes disappeared. Geologists came to see that the fashioning of the earth's surface had been going on for a long time, and is still in progress. The law of evolution, they have found, holds true for the crust of the globe just as it does for the myriad tribes of plants and animals that clothe and people it. It is no longer doubted that the existing configuration of the land has resulted from the action of forces that are still in operation, and by observation and reasoning the history of the various phases in the evolution of surface-features can be unfolded. No doubt the evidence is sometimes hard to read in all its details, but its general bearing can be readily apprehended. The salient facts, the principal data, are conspicuous enough, and the mode of their interpretation is in a manner self-evident.

In setting out upon our present inquiry, however, it is obvious that we ought, in the first place, to know something about rocks and the mode of their arrangement. We must make some acquaintance with the composition and the structure or architecture of the earth's crust before we can form any reasonable conclusion as to the origin of its surface-features. Now, so far as that crust is accessible to observation, it is found to be built up of two kinds of rock, one set being of igneous origin, while the other appears to consist mainly of the products of water action. These last are typically represented by such rocks as conglomerate, sandstone, and shale, which are only more

or less ancient sediments, formed and accumulated in the same way as the gravel, sand, and mud of existing rivers, lakes, and seas. Another common rock of aqueous origin is limestone, of which there are countless varieties—some formed in lakes, like the shell-marls of our own day; others representing the calcareous ooze and coral-reefs of ancient seas; while yet others are obviously chemical precipitates from water surcharged with carbonate of lime. Now and again, also, we meet with rocks of terrestrial origin, such, for example, as many beds and seams of peat, lignite, and coal, which are simply the vegetable *débris* of old land-surfaces. To these land-formed beds we may add certain sandstones of wind-blown origin—indurated sand-dunes, in short.

The *igneous rocks* consist partly of lavas and fragmental materials which have been ejected at the surface, as in modern volcanoes, and partly of formerly molten masses which have cooled and consolidated below ground. The former, therefore, are spoken of as *volcanic*, the latter as *plutonic* or *hypogene* rocks. As it is useful to have some general name for the rocks which owe their origin to the action of epigene agents (*i. e.*, the atmosphere, terrestrial water, ice, the sea, and life), we may term these *derivative*, since they have been built up chiefly out of the relics of pre-existing rocks and the *débris* of plants and animals. By-and-by we shall learn that igneous and derivative rocks have in certain regions been subjected to many remarkable changes, and are in consequence so

altered that it is often hard to detect their original character. These altered masses form what are called the *metamorphic* rocks. They are typically represented by such rocks as gneiss, mica-schist, clay-slate, etc.

The derivative rocks, with which in many regions igneous rocks are associated, occupy by far the larger portion of the land-surface, entering abundantly into the composition of low grounds and mountains alike. Most of these derivatives are sedimentary accumulations, and very many are charged with the remains of animals and plants. By noting the order in which such stratified deposits occur, and by comparing and correlating their fossils, geologists have been able to group them into a series of successive systems, the oldest being that which occurs at the bottom of the series.[1] The united thickness of the several systems probably exceeds twenty miles, but it must not be supposed that all these occur together in any one region. Many broad acres of the earth's surface are occupied by the rocks belonging to one system only. In other countries two or more systems may be present. Again, each individual system is of very variable thickness—swelling out here, thinning off there: in some lands being represented by strata many thousands of feet in thickness, in others dwindling down to a few yards. In short, we may picture to ourselves each system as consisting of a series of larger and smaller lenticular sheets, irregularly distributed over

[1] See Appendix for Table of Geological Systems.

the earth's surface. The various systems thus frequently overlap, the younger stealing over the surface of the older so as often to bury these out of sight.

The metamorphic rocks do not appear at the surface over such extensive areas as those just referred to. Nevertheless, they are widely distributed, and now and again overspread continuously vast regions. The enormous tract that extends from the Great Lakes of North America to the shores of the Arctic Ocean is almost entirely occupied by them. Another immense area of crystalline schistose rocks is met with in Brazil. The Highlands of Scotland, the Scandinavian Peninsula, and North Finland are in like manner largely composed of them, and the same is the case with many parts of Africa, Asia, and Australia. It is further noteworthy that similar rocks form the backbones of most of the great mountain chains of the globe. As already indicated, metamorphic rocks are of various origin, some of them being primarily of igneous and others of aqueous formation. Those which form the nuclei of the youngest mountain chains are sometimes of relatively recent age, while those occupying such broad tracts as Brazil, the Canadian uplands, etc., are of vast antiquity. Crystalline schistose rocks, with associated granites and other igneous rocks, seem everywhere to underlie the sedimentary fossiliferous formations. Very often the latter are separated by a broadly marked line of demarcation from the schists, granites, etc., upon which they repose. In other cases the sedimentary rocks

become gradually altered as they are traced downwards, until eventually they themselves assume the aspect of crystalline schists, penetrated here and there by granitoid igneous rocks.

The origin of those ancient crystalline schists has been much discussed, but does not concern us here. Some geologists have maintained that the rocks in question represent the original cooled crust of the globe, while the majority consider them to be all metamorphic. It is enough for our present purpose to know that a pavement of such rocks appears everywhere to underlie the sedimentary fossiliferous formations.

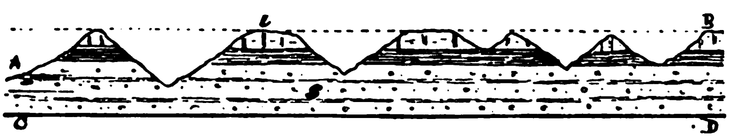

FIG. I. SECTION OF HORIZONTAL STRATA.

The upper continuous line, *A-B*, = surface of ground ; the lower continuous line, *C-D*, = sea-level ; *l*, limestone ; *s*, sandstones and shales.

The great bulk of the derivative rocks being of sedimentary origin, it is obvious that they must have been at the time of their formation spread out in approximately horizontal layers upon the beds of ancient lakes and seas. This we are justified in believing by what we know of the accumulation of similar sediments in our own day. The wide flats of our river-valleys, the broad plains that occupy the sites of silted-up lakes, the extensive deltas of such rivers as the Nile, the Po, the Amazon, the Mississippi, the narrow

or wide belts of low-lying land which within a recent period have been gained from the sea, are all made up of various kinds of sediment arranged in gently inclined or approximately horizontal layers. Now, over considerable areas of the earth's surface the derivative rocks show the same horizontal arrangement, a structure which is obviously original. And this is frequently the case with younger and older sedimentary strata alike. Here, for example (Fig. 1), is a section across a country, the superficial rock-masses of which are horizontally arranged.

The upper line of the section (*A–B*) represents, of course, the surface of the ground, while the lower we shall take to be the level of the sea. The section thus shows the geological structure or arrangement of the rocks from the surface down to the level of the sea. The strata represented consist of a great series of sandstones and shales with one prominent bed of limestone (*l*) at the top. In this case we cannot doubt that the horizontal bedding is original—that the strata were accumulated one above the other in the same order as we see them.

Although such horizontal arrangements are of common enough occurrence, and now and again characterise the sedimentary systems over wide areas, yet, as a general rule, strata tend to be inclined. In many regions the inclination, or *dip*, as it is termed, is sometimes very high—not seldom indeed the beds are seen standing on end, like rows of books in a library. This last appearance of extreme disturbance is not confined

to the strata of any system; nevertheless, it is more characteristic of the older than the younger systems. In the sequel we shall have to study these and other rock-structures more particularly, but for the present we need not do more than make some general acquaintance with them.

A very common arrangement is shown in the next diagram (Fig. 2). Here the strata are arranged in the form of a truncated arch, or *anticline*. At X the

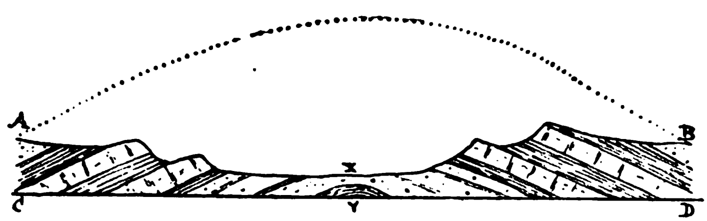

FIG. 2. SECTION ACROSS AN ANTICLINE.

The upper continuous line, A-B, = surface of ground; the lower continuous line, C-D, = sea-level; X-Y, = vertical axis.

beds are approximately horizontal, but from this point they dip on the right towards B, and on the left in the direction of A. Note further that the angle of inclination is the same on each side of the anticline; in other words, the anticlinal axis (X–Y) is vertical. From A to B the distance we shall suppose is six miles.

The succeeding section (Fig. 3) we shall take to be of equal length. Here we have a succession of anticlines, or saddle-backs, separated one from another by troughs, or *synclines*, as they are termed. In other

words, the strata are undulating. From these sections we learn that folds or undulations vary considerably in width. In the region represented by Fig. 2 we have an area six miles in breadth, consisting of a thick series of strata disposed in the form of one single arch or anticline; while in Fig. 3, representing

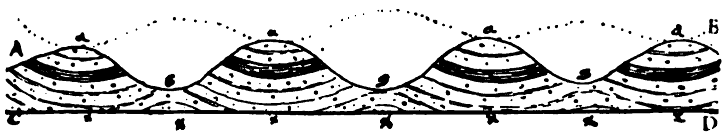

FIG. 3. SECTION ACROSS SYMMETRICAL ANTICLINES AND SYNCLINES.
Upper continuous line, *A*–*B*, = surface of ground; lower continuous line, *C*–*D*, = sea-level; *a a*, anticlines; *s s*, synclines; *a x*, *s x*, axes of folds.

an equal area, the strata are folded into a series of several anticlines and synclines. In both regions the anticlines are *symmetrical;* that is to say, their axes (*a x*, *s x*) are vertical.

But folds or undulations may follow each other much more rapidly than is shown in the preceding section. In countries built up of steeply inclined

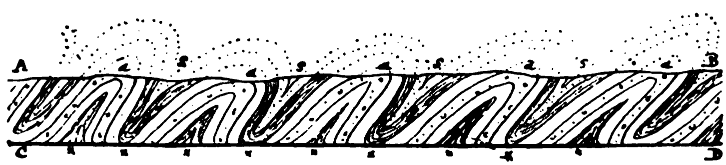

FIG. 4. SECTION ACROSS UNSYMMETRICAL ANTICLINES AND SYNCLINES.
Upper continuous line, *A*–*B*, = surface of ground; lower continuous line, *C*–*D*, = sea-level; *a x*, *s x*, axes of folds.

rocks, the undulations of the strata are more abrupt, and the axes of the folds are frequently inclined. In

Fig. 4, for example, most of the anticlines and synclines lean over to one side, and this to such a degree, that here and there upper beds are doubled under older beds of the same series of strata; in other words, the order of succession appears to be inverted.

From the fact that strata are generally inclined from the horizontal, and frequently curved and folded, it is obvious that they have been subjected to the action of some great disturbing force, for folding and

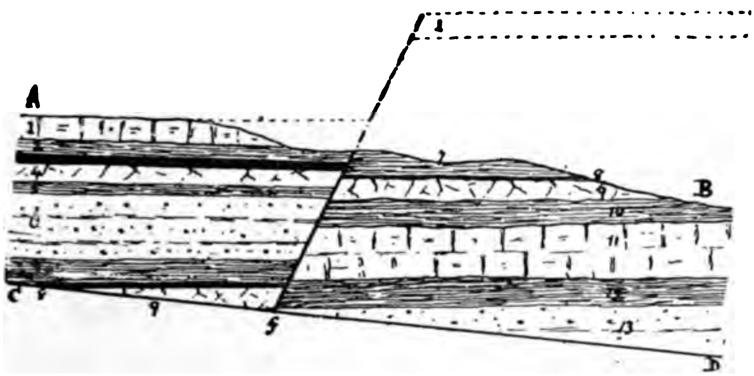

FIG. 5. SECTION ACROSS FAULTY OR DISLOCATED STRATA.

f, normal fault, inclined in the direction of downthrow.

contortion may affect masses of strata many thousands of feet in thickness. Another evident mark of disturbance is furnished by the presence of dislocations, or *faults*, as they are technically termed, along the line of which the rocks have been shifted for, it may be, hundreds and sometimes even for thousands of feet. One of the simplest kind of faults is shown in

the preceding illustration (Fig. 5). Here, as in preceding figures, the upper line (*A–B*) represents the surface of the ground. At *f* the strata are traversed by a fault, which has caused a vertical displacement of the beds to the extent of, say, 500 feet, for it is obvious that the coal and fireclay (8, 9), and the strata amongst which they lie on the left-hand side, were formerly continuous with the corresponding beds on the other side of the fault.

From the facts now briefly set forth we may draw certain conclusions. In the first place, the extensive geographical range of the derivative rocks, most of which are of marine origin, must convince us that the greater portion of our continental areas has been under water. It is not to be understood, however, that all the land-surfaces occupied by sedimentary strata have been submerged at one and the same time. On the contrary, the several geological systems have been accumulated at widely different periods. This is a point, however, to which we shall return: for the present, we need only keep in view the prominent fact that the existing land-surfaces of the globe are composed most frequently of marine strata. There are apparently only two ways in which this phenomenon can be accounted for, and these explanations come to much the same thing. Either the general level of the ocean has fallen, or wide areas of the sea-floor have been pushed up from below and converted into dry land. Both changes appear to have taken place. The bed of the sea has sunk from time to

time to greater and greater depths, and has thus tended to draw the water away from the surface of what are now continental areas. But if the earth's crust under the ocean has subsided, it has also been elevated within what are now dry lands again and again. The folds and corrugations of the strata, and the numerous dislocations by which rocks of all kinds are traversed, clearly demonstrate that movements of the solid crust have taken place. Such crustal disturbances are probably in chief measure due to the fact that the earth is a cooling body. As the solid crust sinks down upon the cooling and contracting nucleus, it must occupy less superficial space. Hence its rocky framework becomes subjected to enormous tangential squeezing and compression to which it yields by bending and folding, by fracture and displacement.

Obviously, then, the mysterious subterranean forces must have played an important part in the formation of earth-features. Disturbed rocks are of more frequent occurrence than strata which have retained their original horizontality. It is no wonder, therefore, that for a long time the general configuration of the land was believed to have been impressed upon it by plutonic agency. Indeed, in the case of certain mountain chains, we cannot fail to see that the larger features of such regions often correspond to a considerable extent with the main flexures and displacements of the underlying rocks. In many elevated tracts, however, composed of highly disturbed and contorted strata, no such coincidence of surface-feat-

ure and underground structure can be traced. The mountain ridges do not correspond to great swellings of the crust; the valleys neither lie in trough-shaped strata, nor do they coincide with gaping fractures. Again, many considerable mountains are built up of rocks which are not convoluted at all, but arranged in horizontal beds. More than this, many plateaux and even lowlands are composed of as highly flexed and contorted strata as are to be met with in any mountainous country. Evidently, therefore, crustal movement is not the only factor in the production of surface-features.

The sections already given will serve to illustrate the general fact that underground structure and superficial configuration do not necessarily correspond. Thus in Fig. 1 we have a series of pyramidal mountains developed in horizontal strata. The slope of the surface, therefore, frequently bears no relation to the "lie" of the beds below. This is further illustrated in the succeeding figures, where we find depressions at the surface, while the rocks immediately underneath show an anticlinal arrangement; and, conversely, where the strata are trough-shaped the surface-feature is not a depression but an elevation.

In the case of the horizontal strata shown in Fig. 1 we have no difficulty in perceiving that the present surface is not that of original deposition. It is impossible that sedimentary deposits could have been piled up in the shape of great pyramids: obviously the beds were formerly continuous, as shown by the dotted lines. Clearly some "monstrous cantles" have been cut out

and removed. And the same is necessarily true of the folded strata. In each case (Figs. 2, 3, 4) masses of strata have disappeared; the tops or backs of the anticlinal arches have been more or less deeply incised, and the material carried away. In subsequent pages it will be shown that the thickness of rocks thus removed can be proved to amount in many cases to thousands of feet.

Not less striking is the evidence of rock-removal furnished by the phenomena of faults. At the surface there may be no inequality of level corresponding to that seen below (see Fig. 5). Obviously, however, a considerable thickness of rock has vanished. Were the missing continuations of the strata to be replaced upon the high side of the fault, they would occupy the space contained within the dotted lines above the present surface *A–B*. Such dislocations often interrupt the continuity of the strata in our coal-fields. In such regions we may traverse level or gently undulating tracts, and be quite unconscious of the fact that geologically we have several times leaped up or jumped down hundreds of feet in a single step. Nay, some rivers flow across dislocations by which the strata have been shifted up or down for thousands of yards, and in some places we may sit upon rocks which are geologically more than a thousand fathoms below or above those on which we rest our feet. Faults, then, afford clear evidence of the wholesale removal of rocks from the surface of the land.

Such proofs of rock-removal can be appreciated by

anyone, and will come frequently before us in the discussion that follows. There is another kind of evidence, however, leading to the same general conclusion, which may be briefly touched upon at this stage of our inquiry. In this and other countries there are enormous masses of rock, often widely extended, which have cooled and consolidated from a state of igneous fusion. Some of these, it is well known, have flowed out as lavas at the surface, while others were never so erupted, but have solidified at greater or less depths below ground. Among the latter is granite, a rock believed to be of deep-seated origin. Its plutonic character is evinced not less by its composition and structure than by its relation to the rock-masses that surround it. Every mass of granite, then, has cooled and consolidated, probably very slowly, and certainly at a less or greater depth in the earth's crust. When this rock is met with over a wide area at the actual surface, therefore,—forming, it may be, great mountains or rolling and broken lowlands,—we know that in such regions thick masses of formerly overlying rocks have been removed. The granite appears at the surface simply because the covering of rocks underneath which it cooled and solidified has been subsequently carried away.

The occurrence at the surface of crystalline schists and other metamorphic rocks has a similar significance. Although the processes by which rocks become so highly altered are still more or less obscure, yet there can be no doubt that the metamorphism had taken

place when the rocks affected were more or less deeply buried in the crust.

While we may safely infer, from the general phenomena of geological structure, that earth-movements have shared in the production of surface-features, we must be convinced, at the same time, that some other factor has aided in the work of shaping out our lands. Earth-movements quite account for the folding and fracturing of strata, for the uplifting of great mountain masses, but they cannot have caused the general loss which these masses have sustained. We may conceive it possible that subterranean action may now and again have resulted in wide-spread shattering of rocks at the surface, but such action could not have caused the broken material to disappear. Further, when we bear in mind that the thickness of rock removed from the surface of the land is sometimes to be measured by many thousands of feet, or even yards, we see at once that subterranean action cannot have been directly implicated in the spoliation of the land. How, then, have anticlines been truncated? What power has removed the strata from the high side of a fault? What, in a word, has produced that truncation and discontinuity of beds which is so common a feature of derivative rocks all the world over? And how shall we account for the presence at the surface of deep-seated plutonic rocks and metamorphic masses? When we have satisfactorily answered such questions we shall have solved the problem of the origin of surface-features.

CHAPTER II

AGENTS OF DENUDATION

CHEMICAL COMPOSITION OF ROCKS—EPIGENE AGENTS—INSOLATION AND DEFLATION—CHEMICAL AND MECHANICAL ACTION OF RAIN—ACTION OF FROST; OF PLANTS AND ANIMALS; OF UNDERGROUND WATER; OF BROOKS AND RIVERS—RATE OF DENUDATION—DENUDATION AND SEDIMENTATION GO HAND IN HAND.

THE present, geologists tell us, contains the key to the past. If we wish to find out how rocks have been removed, and what has since become of them, we must observe what is taking place under the influence of existing agents of change. How, then, are rocks being affected at present? We do not proceed far in our investigation before we discover that they are everywhere becoming disintegrated. In one place they are breaking up into angular fragments; in another, crumbling down into grit, sand, or clay. Brooks and rivers and the waves upon our coasts are constantly undermining them; everywhere, in short, rocks are being assaulted and reduced. But in order to bring this fact more forcibly before the reader, it will be well to sketch, as briefly as may be, the general character of the warfare which is being waged against

rocks over all the land-surface, and to note the various results that flow from this incessant energy of the epigene or superficial agents of change.

As these agents are often associated in their work, it is sometimes hard, or even impossible, to say which has played the most effective part in the demolition of rocks. Nevertheless, it will conduce to clearness if we endeavour to consider the operation of each by itself, so far, at least, as that is possible. Before doing so, however, we must glance for a moment at the general characters of rocks. We have already taken note of the fact that rocks are of various origin —igneous, derivative, and metamorphic. It is now necessary to consider their composition and structure, for, according as these differ, rocks are variously affected by epigene agents, some yielding rapidly, others being more resistant. We need not go into detail. Their composition and structure may be described in the most general terms. For our purpose it will suffice to group them roughly under these four heads: Felspathic, Argillaceous, Silicious, and Calcareous rocks. This is very far from being an exhaustive classification, but under these groups may be included all the rocks that enter most largely into the formation of the earth's crust.

1. *Felspathic Rocks.* These rocks contain as their dominant constituent the mineral, or, rather, the family of minerals, known under the name of felspar. The group includes nearly all the igneous and most of the metamorphic rocks. The derivative rocks that

come under the same head are of relatively small importance. The minerals entering most abundantly into the composition of the felspathic rocks are the *felspars* (aluminous silicates of potash, soda, and lime), various ferro-magnesian silicates, such as *mica*, *pyroxene*, *hornblende*, and *olivine* (aluminous silicates of magnesia, lime, iron-oxides, etc.), and *quartz* (silica, silicic acid). The crystalline igneous rocks occur either in more or less regular beds (lavas), interstratified with derivative rocks, or they penetrate these in the form of irregular veins, dykes, sheets, or large amorphous masses. The lava-form rocks are often associated with beds of volcanic *débris* (tuff, etc.). Some igneous rocks are smoothly compact in texture, such as obsidian and pitchstone, which are simply varieties of volcanic glass; others, such as basalt, consist partly of glass and partly of crystalline ingredients, and vary in texture from compact to coarse-grained; yet others are built up wholly of crystalline substances, and may be fine-grained or very coarsely granular, as granite. The crystalline schists are equally variable as regards texture. They differ, however, from the igneous rocks in structure. While the latter are confusedly crystalline, the schists show a kind of streaky structure or pseudo-lamination, their constituent minerals being arranged in rudely alternate lenticular layers.

Igneous rocks and schists are traversed by cracks and fissures which usually ramify irregularly in all directions. In many bedded igneous rocks (lavas),

however, these cracks, or "joints," as they are termed, are somewhat more regular, being, as a rule, disposed at approximately right angles to the planes of bedding. In certain fine-grained rocks, such as basalt, the jointing is often very regular, giving rise to a prismatic columnar structure, as in the basalts of Staffa and the Giant's Causeway. The main fact, however, with which we are at present concerned is simply this: that all crystalline, igneous, and schistose rocks are traversed by cracks and fissures of one sort or another. It is further to be noted that these rocks, in common with rocks of all kinds, are more or less porous, and therefore liable to be permeated, however slowly, by percolating water.

2. *Argillaceous Rocks.* These rocks are composed chiefly of clay, but other ingredients are usually present. Some are soft, such as ordinary brick-clay; others are of firmer consistency, and frequently show a fine fissile structure, as in common argillaceous shale; yet others are hard, tough rocks, some of which are capable of being cleaved into thin plates, as roofing-slate.

3. *Silicious Rocks.* These might be described in general terms as gravel-and-sand rocks. The most abundant and widely distributed rocks of this class are the sandstones—composed generally of grains of quartz (silica) cemented together by carbonate of lime, by iron-oxide, or other substance. Cementing material, however, is not always present, some sandstones having been solidified by pressure alone. The

gravel-rocks, or conglomerates, usually consist of rounded fragments of quartz or some hard silicious rock. But to this there are exceptions, the stones in some conglomerates consisting of calcareous or of felspathic rocks or of a mixture of many different kinds. A silicious sandstone which has been more or less metamorphosed is termed quartz-rock.

4. *Calcareous Rocks.* Under this head are grouped limestones of every kind. They vary in character from soft earthy marls and chalks to hard, granular, crystalline limestones and saccharoid marbles. Some are nearly pure carbonate of lime; others contain larger or smaller percentages of quartz, clay, iron-oxide, and other impurities.

The Argillaceous, Silicious, and Calcareous groups comprise the great bulk of the derivative rocks as well as a few metamorphic rocks. They are all originally of aqueous or sedimentary origin, and generally occur, therefore, in beds or strata. Like the igneous rocks, they are more or less porous, although some—especially the clay-rocks—are much less permeable than others. In addition to the planes of lamination and stratification, which characterise most derivative rocks, there are other natural division-planes or joints which cut across the strata in directions more or less perpendicular to the bedding. More irregular usually are the joints which intersect hard slates and quartz-rock, these being divided generally much in the same way as schists and amorphous masses of crystalline igneous rock.

There are not a few kinds of rock other than those now referred to, but they may be neglected as, from our present point of view, of relatively little importance. Amongst them are rock-salt, gypsum, coal and lignite, ironstones, and other ores. All these, doubtless, are very notable and valuable, but they are neither so abundant nor so widely distributed as the above-described groups ; in short, they occupy a very subordinate place in the architecture of the earth's crust.

We have now to consider how the superficial or epigene agents attack and reduce rocks. And first, we may note that rocks at the surface are everywhere subject to changes of temperature—warmed by day and during summer, cooled at night and during winter. Thus they alternately expand and contract, and this tends to disintegration, for the materials of which they are composed often yield unequally to strain or tension. This is particularly the case with many crystalline felspathic rocks, such as coarse-grained granite, gneiss, and mica-schist—built up, as these are, of minerals that differ in colour, density, and expansibility. Even when a rock is homogeneous in composition, it is obvious that the heating and cooling of the surface must give rise to strain and tension. In countries where there is no great diurnal range of temperature, as in our own latitudes, any rock-changes due to this cause alone are hardly noticeable, since they are masked or obscured by the action of other and more potent agents. But in the rocky deserts of tropical

and sub-tropical regions, bare of verdure and practically rainless, the effects produced by alternate heating and cooling are very marked. The rocks are cracked and shattered to a depth of several inches; the surfaces peel off, and are rapidly disintegrated and pulverised. Wind then catches up the loose material and sweeps it away, leaving fresh surfaces exposed to the destructive action of insolation. More than this, the grit, sand, and dust carried off by the wind are used as a sand-blast to attack and erode the rocks against which they strike. In this manner cliffs and projecting rocks are undermined, and masses give way and fall to the ground, where, subject to the same grinding action, especially towards the base, they eventually assume the appearance of irregular blocks supported upon pedestals. Mushroom-shaped rocks and hills of this kind are common in all desiccated rocky regions.

The transporting action of the wind, or "deflation," as it is termed, goes on without ceasing day and night and during all seasons; and the result is seen in the deeply eroded rocks, enormous masses of which, it can be shown, have been thus gradually removed. The evidence of denudation is conspicuous, but its products have for the most part been carried away. In some places, as Professor Walther remarks of the Libyan Desert, are great walls of granite rising to heights of 6000 feet, but showing no slopes of *débris* below, as would infallibly be present under temperate conditions of climate. In other places, again,

are deeply excavated wâdies containing no beds of gravel, grit, and sand, such as would not fail to show themselves had the depressions in question been formed by water-action alone. Everywhere, deep, cave-like hollows have been worn out in the rocks, and yet these hold no sediment or detritus, but are swept bare. The wind tends, in short, to transport all loose material from the scene of its origin to the borders of the desert.

In latitudes like our own, insolation doubtless shares in the disintegration of rocks, but the most conspicuous agent employed in that work is rain. Rain is not chemically pure, but always contains some proportion of oxygen and carbonic acid absorbed from the atmosphere; and after it reaches the ground organic acids are derived by it from the decaying vegetable and animal matter with which soils are more or less impregnated. Armed with such chemical agents, it attacks the various minerals of which rocks are composed, and thus, sooner or later, these minerals break up. The felspars and their ferro-magnesian associates, for example, are decomposed—the carbonic acid of the rain-water uniting with the alkalies and alkaline earths of those minerals to form carbonates, which are carried away in solution. The silica set free by this operation is also to some extent removed, while the insoluble silicate of alumina, or clay, remains behind. Such insoluble materials are frequently stained yellow-brown or red, owing to the pressure of iron-oxides. In this way felspathic rocks gradually crum-

ble down. Thus, granite, gneiss, basalt, and other rocks largely composed of felspar, usually show a weathered crust, which, according to the nature of the rock and the length of time its surface has been exposed, may vary from less than an inch up to many feet, or even yards, in thickness. Some granites, for example, are reduced to a kind of gritty clay which may be dug with a spade.

Argillaceous and silicious rocks are not so readily affected by the chemical action of rain. Not infrequently, however, when the grains of a sandstone are cemented together by some soluble substance, such as carbonate of lime, the rock will yield more or less readily to the solvent action of the water. All calcareous rocks, in short, tend to fall an easy prey. If they contain few or no impurities, they "weather" with little or no crust; the rock is simply dissolved. Limestones, however, are seldom quite so pure as this, but are usually impregnated in a greater or less degree with quartz, clay, or other substance, which after the carbonate of lime has been removed remains behind to form a crust. The red and brownish earths and clays that so frequently overlie calcareous rocks, such as chalk and limestone, are simply the insoluble residue of masses of rock, the soluble portions of which have been dissolved and carried away by surface-water.

In all regions where rain falls, the result of this chemical action is conspicuous; soluble rocks are everywhere dissolving, while partially soluble rocks

are becoming rotten and disintegrated. In limestone areas it can be shown that sometimes hundreds of feet of rock have thus been gradually and silently removed from the surface of the land. And the great depth now and again attained by rotted rock testifies likewise to the destructive action of rain-water percolating from the surface. This is particularly noticeable in warm-temperate, sub-tropical, and tropical latitudes, where felspathic rocks are decomposed not infrequently to depths of a hundred feet and more. In temperate and northern regions, the amount of rotted rock is rarely so great. The thicker rock-crusts of southern latitudes are supposed to be due to the larger supplies of organic acids derived from the more abundant vegetation. To some extent this is probably true. But there is another reason for the relatively meagre development of rotted rock in temperate and northern regions generally. Those regions, as we shall learn later on, have recently been subjected to glacial conditions. Broad areas of temperate Europe and North America have been scraped bare by ice-sheets, resembling those of Greenland and the Antarctic Circle. In more southern latitudes, the rotted rocks have escaped such abrasion and denudation, and hence it is not strange that we should find them attaining so great a thickness. The decomposed rock-material encountered in the northern parts of Europe and America has been formed for the most part only since the disappearance of glacial conditions, while in southern regions rock-decay has gone

on without interruption ever since those lands came into existence.

The disintegrating action of rain in temperate and high latitudes is greatly aided by frost, and the same is the case in the elevated tracts of more southern latitudes. Rain renders the superficial portions of rock more porous, and thus enables frost to act more effectually; while frost, by widening pores and fissures, affords readier ingress to meteoric water. Water freezing in soils and subsoils and in the interstitial pores and minute fissures of rocks forces the grains and particles asunder, and when thaw ensues the loosened material is ready to be carried away by rain or melting snow and subsequently, it may be, by wind. The same process takes place on a larger scale in the prizing open of joints and the rending asunder of rocks and rock-masses. Hence in Arctic regions and at high levels in temperate and southern latitudes the wholesale shattering of rocks has produced immense accumulations of angular *débris.* To such an extent has this action taken place, that in some countries the rocks are more or less completely buried in their own ruins. By-and-by so great do these accumulations become that frost is unable to get at the living rock. The loose fragments, however, under which it lies concealed, are themselves shattered, crumbled, and pulverised, until they are in a condition to be swept away by wind or melting snow. By this means the solid rock again comes within reach of the action of frost, and so the work of

disruption and disintegration continues. The great heaps or "screes" of rock-rubbish which cloak the summits and slopes of our mountains, and gather thickly along the base of precipice and cliff, have been dislodged by frost and rolled down from above, their progress downward being often aided by torrential rains, melting snow, and the alternate freezing and thawing of the saturated *débris* itself.

Some reference has already been made to the indirect action of plants in the disintegration of rocks. The various humus acids, as we have seen, are powerful agents of chemical change. Without their aid rain-water would be a less effective worker. The living plants themselves, however, attack rocks, and by means of the acids in their roots dissolve out the mineral matters required by the organisms. Further, their roots penetrate the natural division-planes of rocks and wedge these asunder; and thus, by allowing freer percolation of water, they prepare the way for more rapid disintegration. Nor can we neglect the action of tunnelling and burrowing animals, some of which aid considerably in the work of destruction. There can be no doubt, for example, that worms, as Darwin has shown, play an important part in the formation of soil, which is simply rotted rock plus organic matter.

We see, then, that the disintegration and decomposition of rocks is a process everywhere being carried on—from the crests of the mountains down to the sea, and in every latitude under the sun. No exposed

rock-surface escapes attack. In parched deserts as in well-watered regions, in the dreary barrens of the far north as in the sunny lands of the south, at lofty elevations as in low-lying plains, the work of rock-waste never ceases. Here it is insolation that is the most potent agent of destruction; there it is rain aided by humus and carbonic acids; or rain and frost combine their forces to shatter and pulverise the rocks. In latitudes where frost acts energetically, the most conspicuous proofs of rock-waste are the sheets and heaps of *débris* that are ever travelling down mountain-slopes, or gathering at the base of cliff and precipice. In lower latitudes the most impressive evidence of disintegration is the great thickness attained by rotted rock in positions where it is not liable to be readily swept away by running water.

Hitherto we have been considering the superficial parts of rock, as these are affected by weathering. We are not to suppose, however, that the alteration of a rock ceases immediately underneath its crust. Rotted rock is not the only evidence of decay. In the case of felspathic rocks, it is found that some of the constituent minerals, more especially the felspars, usually show traces of decomposition at depths of many feet or even yards below the weathered superficial portions. It is hard, indeed, to get a specimen of any such rock from the bottom of our deepest quarries which is perfectly fresh. Water soaks through interstitial fissures and pores, and finds its way by joints and other division-planes, so that chemical ac-

tion, with resultant rock-decay, is carried on at the greatest depths to which water can penetrate. This underground water eventually comes to the surface again through similar joints, etc., opening upwards, and thus forms natural springs. All these springs contain mineral matter, derived from the chemical decomposition and solution of rock-constituents. Many, indeed, are so highly impregnated, that as soon as they are exposed to evaporation they begin to deposit some of their mineral matter. Thus vast quantities of rock-material are brought up from the bowels of the earth. To such an extent is this the case in certain regions, that the ground is undermined and the surface not infrequently subsides. In countries where calcareous rocks largely predominate, acidulated water filtering down from the surface through fissures and other division-planes has often licked out a complicated series of tortuous tunnels and galleries. So far has this process been carried on in some regions that the whole rainfall finds its way into subterranean courses, and the entire drainage of the land is conducted underground. The dimensions attained by many well-known limestone caverns, and the great width and depth of the channels through which subterranean rivers reach the sea, help us to appreciate the amount of rock-material which underground water is capable of removing. When we add to this all the mineral matter leached out at the surface and carried away by streams and rivers, it is obvious that in course of time the land cannot fail to have been con-

siderably modified by chemical action alone. In point of fact, it can be shown that from the surface of certain regions hundreds of feet of various calcareous rocks have thus been gradually removed; while in other cases the contour of the ground has been notably affected by the collapse of underground channels and chambers. But if the results of the chemical action of meteoric water be most evident in places where calcareous rocks predominate, yet the thickness attained in other countries by the crusts of less soluble rocks shows plainly enough that the whole land-surface of the globe is affected by the same action.

We may now consider the mechanical action of terrestrial water, by means of which the more or less insoluble residue of disintegrated rock is removed. Weathered rock is generally very porous, and is thus readily pulverised by frost. Some crusts crumble away as they are formed, while others adhere more persistently. On slopes and in mountain-regions generally, decomposed and disintegrated materials are seldom allowed to remain long *in situ*—rain and melting snow soon sweep away the finer portions. Great thicknesses of rotted rock are, therefore, somewhat exceptional in such places. Where, on the other hand, the land-surface is plain-like, or gently undulating, and the drainage sluggish, weathered materials are not so readily removed. Nevertheless, under the influence of rain alone, or of rain and melting snow, the products of rock-waste are everywhere travelling,

slowly or more rapidly, according to circumstances, from higher to lower levels. In temperate latitudes, where the rainfall is distributed over the year, this transference of material is not so conspicuous as in countries where the rainfall is crowded into a short season. Even in our own country, however, one may observe how in gently undulating tracts rain washes the finer particles down the slopes and spreads them over the hollows. After exceptionally heavy or long-continued rain this process becomes intensified—fine mud, silt, sand, and grit are swept into the brooks and streams, and the swollen rivers run discoloured to the sea. Similar floods often result from the melting of snow in spring. During such floods our rivers are generally more turbid than when they are swollen merely by heavy or continuous rain. When thaw ensues weathered rock-surfaces crumble down, while superficial accumulations of disintegrated materials become more or less saturated by melting snow. To such a degree is this soaking sometimes carried, that the whole surface of sloping fields may be set in motion. The soils creep, slide, and occasionally flow. Not infrequently also the subsoils and disintegrated rock-surfaces on steep inclinations collapse and slide into the valleys. Everyone, in short, is familiar with the fact that flooded rivers are invariably muddy, and that the mud or silt which discolours them has been abstracted from the land.

In temperate lands of small extent like England the rivers are under ordinary conditions somewhat clear.

But in continental tracts the larger rivers are always more or less turbid. This is due to many causes. Some rivers, for example, head in glaciers, and are thus clouded at their very origin. Others, again, cross several degrees of latitude, and traverse different climatic regions. Hence it will rarely happen that snow is not melting or rain falling in some part of a great drainage-area. Many rivers, again, after escaping from the mountains, flow through countries the superficial formations of which are readily undermined and washed away, and thus the main stream and its affluents become clouded with sediment. It is in tropical and subtropical latitudes, of course, that the most destructive effects of rain are witnessed. During the wet season the rivers of such regions discharge enormous volumes of mud-laden water.

We may conclude, then, that under the influence of atmospheric agents rocks are everywhere decomposed and disintegrated; and, further, that there is a universal transference from higher to lower levels of the materials thus set free. Now and again, it is true, there may be long pauses in the journey—the materials may linger in hollows and depressions. Eventually, however, they are again put in motion, and by direct or circuitous route, as the case may be, find their way into the rivers, and finally come to rest in the ocean. The river-systems of the world, then, are the lines along which the waste products of the land are carried seawards. But rivers are much more than mere transporters of sediment. Just as in desert

lands wind employs disintegrated rock-material as a sand-blast, so rivers use their stones, grit, and sand as tools with which to rasp, file, and undermine the rocks over which they flow. In this way their channels are gradually deepened and widened. Some of the transported material is held in solution, part is carried in mechanical suspension, and another portion is pushed and rolled forward on the bed. It is the solid ingredients, of course, that act as eroding agents. While much of the finer sediment finds its way into the drainage-system by the agency of rain and melting snow, the coarser materials are derived chiefly from the destruction of the rocks that underlie or overhang the course of a river and its feeders. In temperate and northern latitudes natural springs and frost are responsible for much of the rock *débris* which cumbers the beds of streams, but much also is dislodged by the undermining action of the water itself. Rock-fragments when first introduced are more or less angular, but as they travel down stream they often break up into smaller pieces along natural cracks or joints, and the sharp corners and edges of these get worn away by mutual attrition, and by rasping on the rocky bed. In this manner the several portions gradually become smoothed and rounded—the process of abrasion resulting necessarily in the production of grit, sand, silt, etc. Thus in a typical river-course, consisting of mountain-track, valley-track, and plain-track, we note a progressive change in the character of the sediments as the river is followed from its

source to the sea. In the mountain-track, where the course is steep and usually in a rocky channel, angular and subangular fragments abound, and the detritus generally is coarse. In the valley-track, the inclination of which is gentle, well-rounded gravel, with grit and sand, predominate, the latter becoming more plentiful as the plain-track is approached. In the plain-track the prevailing sediments are fine sand and silt.

The amount of material removed by a river depends on the volume of the water, the velocity of the current, and the geological character of the drainage-area. Thus, the larger the river, other things being equal, the greater the burden of sediment. Again, a rapid current transports material more effectively than a gentler stream, while rivers that flow through lands whose rocks are readily eroded carry more sediment than rivers of equal volume and velocity traversing regions of more resistant rocks. Should a lake interrupt the current of a river, all the gravel, sand, and mud may be intercepted, and the stream will then issue clear and pellucid at the lower end of the lake, as the Rhone does at Geneva. The lake, in short, acts as a settling reservoir. By and by, however, the lacustrine hollow becomes silted up and converted into an alluvial flat, through which the silt-laden water winds its way towards the ocean. Reaching that bourn, the current of the river is arrested, and its sediment thrown down. Should no strong tidal current sweep the coast, removing sediment as it ar-

rives, the sea becomes silted up in the same way as the lake, and in time a delta is formed. The growth of the latter necessarily depends partly on the activity of the river and partly upon the depth of the estuary and the action of waves and tidal currents. But if nothing interrupted the growth of a delta—were all the materials brought down by a river to accumulate at its mouth—it is obvious that the rate of increase of a delta would enable us to form an estimate of the rate at which the drainage-area of the river was being eroded. It is certain, however, that such conditions never obtain. Even in the quietest estuaries much of the sediment is carried away by the sea. The rate of delta-growth must be exceeded by that of fluviatile transport.

Geologists, however, have adopted another method of estimating the loss sustained by the land. They can measure the amount of material held in solution, and of solid matter carried in suspension and rolled forward on the bed of a river. As might have been expected, the amount varies with the season of the year in each individual river, while different rivers yield very different results. But even in the case of the least active streams the transported material is much more considerable than might have been supposed. Hence one need not wonder that in spite of obstacles the deltas of many rivers advance seawards more or less rapidly. The delta of the Rhone, for example, pushes forward at the rate of about 50 feet annually, while that of the Po increases by more than

70 yards, and that of the Mississippi by 80 to 100 yards in the same time.

It is sufficiently obvious that the material carried seawards by rivers must afford some indication of the rate at which the surface of the land is being lowered by subaërial action. Having ascertained the annual amount discharged by any individual river, we learn, at the same time, to what extent the drainage-area of that river is being denuded. In the case of the Mississippi, for example, it has been calculated that the amount of sediment removed is equal to a lowering of the whole drainage-area by $\frac{1}{6000}$th of a foot. In other words, could we gather up all the material discharged in one year, and distribute it equally over the wide regions drained by that river and its tributaries, we should raise the land-surface by $\frac{1}{6000}$th of a foot. That does not seem to be much, but at this rate of erosion one foot of rock will be removed from the Mississippi basin in 6000 years; and the Mississippi is not so active a worker as many other rivers. An average of many estimates of the similar work performed by rivers in all quarters of the globe shows that the rate at which drainage-areas generally are being lowered is one yard in 8000 to 11,000 years. It must not be supposed that this erosion is equal throughout any drainage-area. As a rule, denudation will take place most rapidly over the more steeply inclined portions of the ground. On mountain declivities and hill slopes rock-disintegration and the removal of waste products will proceed more actively than upon low

grounds and plains. The work of erosion will be carried on most effectively in the torrential tracts of streams and rivers. Indeed, we may say that it is in valleys generally that we may expect to find the most cogent evidence of erosion now in action.

A little consideration will show that the estimates just referred to do not tell us all the truth concerning denudation. They show us only the amount of waste material which is swept into the sea. They afford no indication of the actual amount of rock-disintegration and erosion. Rock-rubbish gathers far more rapidly in mountain-regions than it can be removed by running water. Indeed, over a whole land-surface rocks are disintegrated and *débris* accumulates from year to year. Nor is the amount of material brought down by a river to its mouth an index even to the activity of the river itself as a denuding and transporting agent. Enormous volumes of detritus are deposited in valleys or come to rest in lakes and inland seas.

Hitherto we have been treating of the work done by the atmosphere and running water. Some reference has also been made to frost as a potent disintegrator of rocks. But we have still to consider the action of glaciers in modifying the surfaces over which they flow. It can be shown that valleys have been widened and deepened, and broad areas more or less remodelled, by flowing ice, so that glaciers must not be ignored in any general account of denuding agents. It will be more convenient, however, to leave them for the present; for however interesting and import-

ant their action may be, it is yet of minor consequence so far as the origin of surface-features as a whole is concerned. For similar reasons we may delay the consideration of marine erosion. The action of the sea upon the land is necessarily confined to a narrow belt, whereas that of the subaërial agents affects the whole surface of the land.

We may take it that the denudation of the surface, rendered everywhere so conspicuous by the discontinuity of strata, has been effected mainly by the atmosphere and running water. Other agents have, no doubt, played a part, but those just referred to must be credited with the chief share in the work of erosion. Such is the general conclusion to which we are led by the study of causes now in action. And observation and reflection combine to assure us that subaërial erosion has been equally effective during the formation of all the derivative rocks which enter so largely into the framework of the earth's crust. For these rocks are for the most part of sedimentary origin—they tell us of ancient lakes, estuaries, and seas. All their materials have been derived from the degradation of old land-surfaces, partly no doubt by the sea, but in chief measure by subaërial agents. And the great thickness and extent attained by many of the geological systems enable us to form some idea of what is meant by denudation. What, for instance, shall we say of a system composed essentially of sedimentary strata reaching a thickness of several thousand feet, and occupying an area of many thousand

square miles? Obviously, the materials of such a system have been derived from the waste of ancient lands. Mountain-masses must have been disintegrated, and removed in the form of sediment, and gradually piled up, layer upon layer, on the floor of the sea. Every bed of sedimentary rock, in short, is evidence of denudation.

Further, it has been ascertained that in the building up of the various great geological systems the same materials have been used over and over again. Sediments accumulated upon the sea-bottom have subsequently, owing to crustal movements, entered

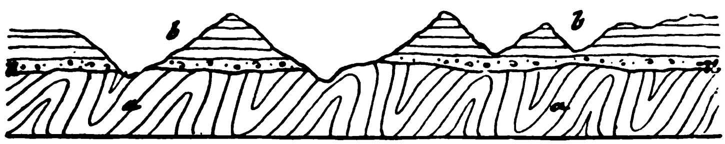

FIG. 6. SECTION ACROSS UNCONFORMABLE STRATA.

a a, beds of sandstone, shale, etc.; *b b*, conglomerates and sandstone resting discordantly or unconformably upon *a a*; *u u*, line of unconformity.

into the formation of a new land-surface, and thereafter, attacked by the epigene agents of change, have again been swept down to sea as gravel, sand, and mud. The history of such changes is easily read in the rock-structure known as *unconformity*. In the accompanying section (Fig. 6), for example, two sets of strata are shown—the upper (*b*) resting discordantly or unconformably upon the lower (*a*). The lower series of sandstones and shales is charged with the remains of marine and brackish-water organisms

and of land-plants. The overlying strata (*b*) are likewise of aqueous origin, and consist chiefly of conglomerates and sandstones below, and of somewhat finer-grained sedimentary beds above. Like the older series (*a*), they likewise contain marine and brackish-water fossils. The beds (*a*) introduce us to an estuary, or shallow bay of the sea, into which sediment is carried from some adjacent land. The whole series has evidently been deposited in water of no great depth, as is shown by the character of the rocks and their fossil contents. And as the strata attain a thickness of more than 2000 feet, we must infer that during their accumulation the sea-floor was slowly subsiding, the rate of sedimentation probably keeping pace with the subsidence. In other words, the bed of the sea appears to have been silted up as fast as it sank, so that relatively shallow-water conditions persisted during the deposition of the land-derived sediments. Then a time came when the sea-floor ceased to sink and another movement of the crust took place, which resulted in the folding of the sedimentary strata and the conversion of the sea-bottom into dry land. The folded rocks were now subjected during some prolonged period to the action of the various subaërial agents of erosion, whereby the whole land-surface was eventually denuded and planed down. When the work of erosion had been so far completed, the entire region again subsided, and formed the bed of a shallow sea. Under these conditions the drowned land-surface became overspread in time with new ac-

cumulations of sediment, derived from the degradation of adjacent areas that still continued above sea-level. The strata (*b*) are in point of fact largely composed of materials derived from the breaking up and disintegration of the underlying series (*a*), just as the latter have themselves been derived from the demolition of pre-existing rock-masses. After the formation of the upper series (*b*) the region was re-elevated, and once more formed a land-surface, which has doubtless endured for a long period, seeing that much erosion has taken place, the horizontal beds having been greatly denuded, trenched, and furrowed, so that at the bottom of deep valleys the underlying older series has been laid bare and eaten into by running water.

Such is the kind of tale which one may read almost everywhere. The very existence of sedimentary strata implies denudation of land-areas—denudation and sedimentation go hand in hand. When we bear in mind that the average thickness of the sedimentary rocks which overspread so large an area of the dry lands of the globe cannot be less than 8000 or 10,000 feet, we cannot fail to be impressed with the magnitude of denudation. And this impression will be deepened when we reflect that the bulk of the materials entering into the composition of the derivative rocks has been used over and over again. The mere thickness of existing sedimentary strata, therefore, is very far indeed from being an index to the amount of erosion which has been effected since the deposition of the oldest aqueous strata.

CHAPTER III

LAND-FORMS IN REGIONS OF HORIZONTAL STRATA

VARIOUS FACTORS DETERMINING EARTH SCULPTURE—INFLUENCE OF GEOLOGICAL STRUCTURE AND THE CHARACTER OF ROCKS IN DETERMINING THE CONFIGURATION ASSUMED BY HORIZONTAL STRATA—PLAINS AND PLATEAUX OF ACCUMULATION.

HITHERTO we have been considering erosion from one point of view only. We glanced first at the general evidence of denudation as furnished by the abrupt truncation and discontinuity of strata, and by the appearance at the surface of rocks which could never have originated in that position. Then we discussed the action of existing agents of change, and saw reason to conclude that the denudation everywhere conspicuous must be the result of that action. Some reference has also been made to the fact that rocks are of various composition and consistency, and therefore tend to yield and crumble away unequally. It follows from this that denudation will be retarded or hastened according as the rocks succumb slowly or more rapidly to the action of eroding agents. Given an elevated plane-surface of some extent, composed

of rocks of different degrees of durability, and it is obvious that such a surface must in time become irregularly worn away. The readily eroded rocks will disappear most rapidly, and thus by and by the plane-surface will be more or less profoundly modified and come to assume a diversified configuration. The relatively hard and resisting rocks will determine the position of the high grounds, while the low grounds will practically coincide with the areas occupied by the more yielding rock-masses.

This we shall find holds true to a large extent of all land-surfaces. Nevertheless, existing configurations have not been determined solely by the mineralogical composition of the rocks. There is yet another factor to be taken into consideration. The form assumed by a land-surface under denudation depends not only on the composition of rocks, but very largely on the mode of their arrangement. Certain rock-structures, as we shall learn, favour denudation, while others are more resisting. So dominant, indeed, has been the influence of geological structure in determining the results worked out by erosion, that without a knowledge of the structure of a country we can form no reliable opinion as to the origin of its surface-features.

But even this is not all. We have likewise to consider the geological history of the land with a view to ascertain what appearance it presented when rains and rivers were just beginning the work of erosion. For it is obvious that the direction of the drainage must

have been determined in the first place by the original inclination of the surface.

Once more, we know that existing land-surfaces have often been disturbed by subterranean action, and that such action has not infrequently led to considerable modification of drainage-systems. It is remarkable, however, how persistent are great rivers in maintaining their direction. When it has been once fairly established, a large river may outlive many revolutions of the surface. River-valleys are not seldom older than the mountain-ridges which they sometimes traverse ; or, to put it in another way, new mountains may come into existence without deflecting the rivers across whose valleys they may seem at one time to have extended—for the rivers have simply sawed their way through the ridges as these were being gradually developed.

The history of the denudation of a land-surface is in truth often highly complicated and hard to read. Many factors have aided in determining the final results of erosion, and it is not always possible to assign to each its proper share in the work. But we may truly say that the sculpture of the land—the form it has assumed under denudation—has been determined mainly by these three factors : (*a*) the original slope of the surface ; (*b*) the geological structure of the ground ; and (*c*) the character of the rocks.

Both hypogene and epigene agents, therefore, have been concerned in the evolution of land-forms. In regions much disturbed by subterranean action within

relatively recent geological times, many of the most striking surface-features are obviously due to deformation and dislocation of the crust. All such features, however, sooner or later become modified by epigene action, and thus it has come to pass that in countries which have existed as dry land for vast periods of time, undisturbed in the later stages of their history by crustal movement, the surface-features are such as only epigene action can account for. Original irregularities of the ground, the result of hypogene action, have been obliterated and replaced by an outline wholly due to denudation.

The existence of fractured and folded strata enables us vividly to realise the fact that hypogene action has played a prominent part in the evolution of land-forms. Not only are many inequalities of the surface the direct result of that action, but even after such irregularities have been removed, the various positions assumed by the flexed and fractured rocks have largely determined the configuration subsequently worked out by the epigene agents of change. Thus both directly and indirectly crustal movements have had a large share in the production of surface-features. It is not necessary for our purpose to inquire into the causes of such movements. In the opinion of most geologists they are due to the secular cooling of the earth. As the nucleus cools it contracts, and the already cooled crust sinks down upon it. This movement necessarily results in the fracturing and wrinkling of the crust, which as it sinks is compelled to occupy

a smaller superficial area. The deformation brought about in this way varies in extent. In some places the general subsidence of the crust has not been marked by much disturbance of the rocks; the original horizontality of the strata has been largely preserved. In other regions the reverse is the case, the strata having been everywhere folded and fractured; and between these two extremes are many gradations.

The various structures assumed by disturbed rock-masses show that crustal movements are of two kinds, horizontal and vertical. Folding and its accompanying phenomena are obviously the result of tangential pressure. Sometimes the strata are so folded as to present the appearance of a series of broad, gentle undulations. At other times the folds are pressed closely together and bent over to one side in the direction of crustal movement. In certain regions so great has been the horizontal thrust, that masses of rock, thousands of feet in thickness, have sheared under the pressure and travelled forwards for miles, older rocks being pushed forward bodily over younger masses. But besides such horizontal movements there are vertical movements of the crust, typically represented by the dislocations known as *normal faults*. Normal faults are more or less vertical displacements, often of small amount, but not infrequently very great. Many are vast rents traversing the crust in some determinate direction, the rocks on one side of the fault having subsided for hundreds or even for thousands of feet. We may reserve for the present,

however, any further discussion of the rock-structures that result from hypogene action. All that we need at present bear in mind is the general fact that the crust of the earth is subject to deformation.

We now proceed to inquire more particularly into the influence of geological structure and the character of rocks upon the development of land-forms. We shall therefore consider first the form assumed by lands built up of approximately horizontal strata. This is the simplest kind of geological structure: the tale it tells is not hard to read. We can follow it from first to last in all its details. But if we succeed in grasping what is meant by the denudation of horizontal strata, we shall have little difficulty in explaining the origin of surface-features in regions the geological structure of which is much more complicated.

As common examples of horizontally bedded strata we may take the alluvial deposits that mark the sites of vanished lakes; the terraces of gravel, sand, and silt that occur in river-valleys; deltas, and raised beaches. Fluvio-marine deposits and raised beaches of recent age generally form low plains rising but a few feet or yards above sea-level. Their inclination is seawards, usually at so low an angle that they often appear to the eye level, or approximately so. This gently sloping surface is an original configuration, for it corresponds with the structure of the various underlying deposits, the general inclination or dip of which is in the same direction as the surface. When that surface is approximately level denudation necessarily

proceeds very slowly, although in time the action of rain alone will suffice to lower the general level. But however much raised beaches and deltas of recent age may have been modified superficially by subaërial denudation, we must admit that their most characteristic features are original, and due to the mode of their formation.

The same holds true to a large extent of recent lacustrine and fluviatile deposits. The wide flats that tell us where lakes formerly existed, and the broad alluvial tracts through which streams and rivers meander, are, like deltas and raised beaches, plains of accumulation. It goes without saying, however, that many of these plains are more or less eroded, and have acquired an undulating, furrowed, and irregular surface. Some alluvial tracts, indeed, have been so cut up by rain and running water that, in the rough, rolling ground over which he toils, the traveller may find it hard to recognise the characteristic features of a plain.

In a broad river-basin alluvial terraces and plains usually occur at various heights, marking successive levels at which the river and its tributaries have flowed while deepening their courses. The lowest terraces and flood-plains are, of course, the youngest, and show, therefore, least trace of subaërial erosion. As we recede from these modern alluvia and rise to higher levels, the terraces and plains become more and more denuded. The highest-lying river-accumulations, indeed, may be so much eaten into and washed down

that only scattered patches may remain, and few or no traces of the original flat surface can then be recognised. Thus fluviatile terraces and recent alluvia all tend to become modified superficially, while at the same time they are undermined and cut into by streams and rivers.

The plains of accumulation at present referred to belong to a recent geological age, and consist for the most part of incoherent deposits, such as gravel, sand, clay, silt, loam, and so forth. And it is worthy of note that the nature of the deposits has to some ex-

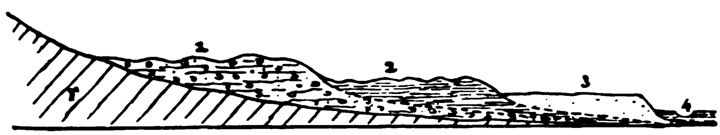

FIG. 7. SECTION ACROSS A SERIES OF ALLUVIAL TERRACES.
r, solid rocks ; 1, oldest terrace ; 2, second terrace ; 3, third and youngest terrace ; 4, river and recent alluvial plain.

tent influenced the denudation of the ground. Thus terraces and plains composed mainly of gravel tend to retain their original level surface, while similar flats of clay and loam of the same age as the gravel have frequently been furrowed and channelled to such an extent that the originally level surface has largely, or even entirely, disappeared. The reason is obvious, for clay and loam are somewhat impervious, while gravel is highly porous. Consequently rain falling on the surface of the latter is rapidly absorbed, and little or no superficial flow is possible. But in the case of the more impervious deposits rain is absorbed very

sparingly, and naturally tends to produce inequalities as it seeks its way over the gently inclined surface.

The origin and present aspect of such recent plains of accumulation are so obvious and so readily accounted for, that it is hardly necessary to do more than cite a few examples. Amongst the most notable are the great deltas of such rivers as the Mississippi, the Amazon, the Rhone, the Po, the Danube, the Rhine, the Niger, the Ganges, etc., and the broad flats and terraces which occur within the drainage-areas of the same rivers. The vast plains of the Aralo-Caspian area, and the far-extended tundras of Northern Siberia, are likewise examples of plains of accumulation, all of which belong to recent geological times. However much some of these plains may have been furrowed and trenched by running water, we yet have no difficulty in recognising that the general form of the surface is due to sedimentation. The deposits of which they are built up have been laid down in approximately horizontal or gently inclined layers, and the even or level surface is thus simply an expression of the arrangement of the bedding. In a word, the geological structure has determined the configuration of the surface.

But it is needless to say that horizontal strata are not confined to low levels, nor do they always consist of unconsolidated materials, like gravel, sand, and clay. Horizontal strata of such rocks as sandstone, shale, limestone, basalt, etc., enter largely into the composition of certain lofty plateaux and mountain-

regions. And they belong, moreover, to very different geological periods, some being of comparatively recent formation, while others date back to ages incalculably remote.

One of the most interesting and instructive regions of the kind is the remarkable plateau of the Grand Cañon district of Arizona and Utah. This plateau occupies an area of between 13,000 and 16,000 square miles, and is traversed by the Colorado River of the West, which follows a tortuous course towards west-south-west through a succession of profound ravines or cañons. The strata visible at the surface are approximately horizontal, and attain a thickness of many thousand feet. It may be said, therefore, that the prevalent plain-like character of the surface is an expression of the underground structure—that, in short, the Grand Cañon district is a plateau of accumulation. This, in a broad sense, is doubtless true; but when we come to examine the configuration and structure of the district more closely, we find reason to conclude that the original surface has been greatly modified by denudation. We learn, moreover, that the strata are not quite horizontal. The inclination is certainly gentle, but a slope of only one degree, if continued for a few miles, will result in a fall of several hundred feet. If a surface be inclined at an angle of one degree, then for every eleven miles of distance it will lose 1000 feet of elevation. Now, in the Grand Cañon district the general inclination of the strata is towards north and

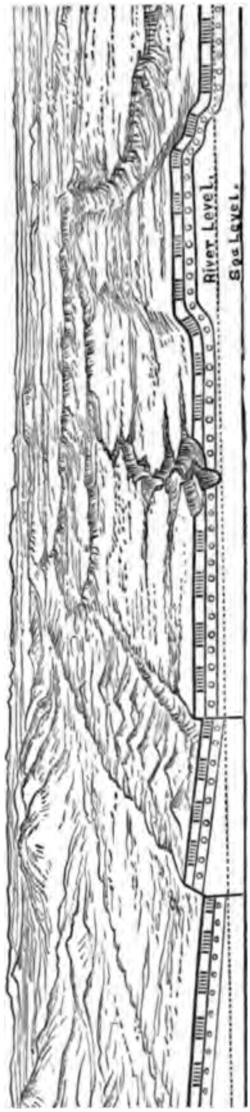

FIG. 8. SECTION AND BIRD'S-EYE VIEW OF COLORADO PLATEAU. (Powell.)
Strata approximately horizontal, but showing a few simple flexures (monoclinal folds) and normal faults.

north-east, while the slope of the surface is in the opposite direction. Thus it comes to pass that strata which lie open to the day upon the south-west margin of the plateau gradually descend towards north and north-east, until, in a distance of 120 miles or thereabouts, they lie buried at a depth of several thousand feet. It is not quite true, therefore, that in the Grand Cañon district the form of the ground is an exact expression of the underground structure. On the contrary, the average slope of the surface is against and not with the average dip of the strata. Nevertheless, it cannot be doubted that the general configuration of the region—its plateau-character—has, in the first place, been determined by the approximately horizontal

disposition of the strata, and that it may be rightly termed a plateau of accumulation. A glance at the geological history of the district will show how far the plateau-character is original, and to what extent and by what means it has been subsequently modified.

Reference has been made to the fact that the rocks composing the plateau are chiefly of aqueous origin, and approximately horizontal.

Here and there in the bottoms of deep cañons we get peeps at another set of rocks that form the pavement upon which the horizontal strata repose. With the history of these older underlying rocks we need not concern ourselves further than to note that they are of Pre-Cambrian and early Palæozoic age. It is with the superincumbent masses that we have to deal. Those attain a vast thickness, and range in age from Carboniferous down to Eocene times. At the beginning of the Carboniferous Period the district formed a portion of the sea-floor, and similar marine conditions obtained during the deposition of all the succeeding systems of strata down to the close of Cretaceous times. Throughout all that long succession of ages the sea would appear never to have been deep, although during the early part of the Carboniferous Period it was probably deeper than in subsequent times. When we consider that the marine sediments reach a united thickness of over 15,000 feet it may at first sight appear impossible that so thick a mass of materials could accumulate in a shallow sea. The explanation, however, is simple enough—sub-

sidence kept pace with sedimentation. Slowly and gradually the bed of the sea went down—slowly and gradually it was silted up by sediments derived from the adjacent land.

At last, towards the close of Cretaceous times, certain new crustal movements began—elevation ensued, and the sea finally retired from the district. An extensive lake now occupied the site of the plateau-country for a prolonged period, during which sediments were washed down as before from the neighbouring uplands, and gathered over the level surface of the Cretaceous marine strata until they had reached a thickness of 5000 feet or more. As these deposits appear likewise to have been laid down chiefly in shallow water, it may be inferred that the slow subsidence of the area which accompanied the accumulation of the underlying marine strata was repeated during the lacustrine period.

The whole region, it will be understood, had been elevated at the close of Cretaceous times; but the movement was differential, the greatest rise having been experienced by the uplands surrounding the lacustrine basin. Eventually the river, escaping over the lower lip of that basin, deepened the outlet and succeeded in draining the lake, which was then replaced by an alluvial plain. At this stage the nearly level surface of the drained lake-bed sloped gently from east-north-east to west-south-west, and thus determined the direction of the primeval Colorado River and its larger tributaries, which headed then

as now in the high lands overlooking the basin. When these waters first began to wander across the alluvial plain, the slope of the surface and the inclination of the underlying sedimentary strata doubtless coincided. But these conditions were ere long disturbed by successive movements of elevation, and the prevalent horizontality of the strata was modified. Here and there the beds were bent or flexed, and traversed by great fractures along which the strata became vertically displaced for thousands of feet. Yet, strange to say, none of these earth-movements succeeded in deflecting the main drainage of the district. The Colorado and its chief affluents continued to flow in the courses they had attained at the final disappearance of the great lake. It is clear, therefore, that the bending and dislocation of the strata must have proceeded very slowly, for the rivers were able to cut their way across both flexures and faults as fast as these showed at the surface.

Before the great lake had vanished some portions of the older marine strata had been elevated, and formed part of the land surrounding the basin. Here they were for a long period exposed to the erosive action of epigene agents, and must have suffered much loss. But all such denudation sinks into insignificance when we consider the magnitude of the erosion which has taken place since the great lake dried up. Fortunately, owing to the simple geological structure of the Grand Cañon district, the amount of that erosion can be readily estimated. According

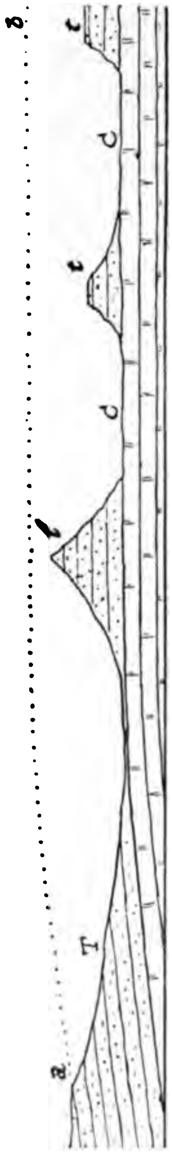

Fig. 9. Diagrammatic Section across Colorado Plateau.
C, Carboniferous strata; *T*, younger strata; *a*...*b*, level formerly attained by plateau; *t t*, remnants of the younger strata *T*.

to Captain Dutton, the average thickness of strata removed from an area of 13,000 to 15,000 square miles cannot have been under 10,000 feet. This may seem a startling conclusion, but it is based on evidence which cannot be gainsaid. Throughout the major portion of the plateau-country horizontal Carboniferous strata occupy the surface. As these are followed northward they gradually dip in that direction under younger strata (Permian, Mesozoic, and Cainozoic rocks), until they are buried at last to a depth of 10,000 feet and more. Now Captain Dutton has shown that this vast thickness of overlying strata formerly extended throughout the whole Grand Cañon district. This is proved by the fact that many outliers or relics of the rocks in question still remain, scattered at intervals over the broad surface of the Carboniferous strata. They form conspicuous table-shaped and pyramidal hills, rising more or less abruptly above the great Carboniferous platform. The accompanying diagram shows the general

relations of those isolated "buttes" and "mesas," as they are termed, to the underlying Carboniferous rocks and the strata at *T*, of which they are detached outliers. The dotted line (*a–b*) indicates the level originally attained by the plateau. All the rock that formerly existed between *a–b* and the surface of the Carboniferous strata (*C*) has been denuded away.

How has this enormous erosion been effected, and what are the more prominent features of the denuded area? A low-lying plain of accumulation, such as a delta, cannot experience much erosion; the surface is approximately level, or has only a very gentle inclination, and any water flowing over it must be sluggish and ineffective. But conceive such a plain upheaved for several hundred feet, and it is obvious that the fall of the river to the sea will then be increased and its erosive action greatly augmented. It will therefore proceed to dig a deeper and wider course for itself. Now let us suppose that an elevated plain is traversed not by one main river only, but by numerous affluents, each with its quota of tributary streams. The running waters will continue to deepen their channels until the gradient by the process is gradually reduced to a minimum and vertical erosion ceases. The main river will be the first to attain this base-level—a level not much above that of the sea. The plain-track will gradually extend from the sea inland until the same low gradient is attained throughout the whole course of the river. In time all the affluents with their tributaries will arrive at the same stage.

But rivers do not only cut vertically; they also undermine their banks and cliffs, and thus erode horizontally; hence it follows that the valleys will be widened as well as deepened. The widening process may be greatly aided by the action of wind, rain, springs, and frost. Not infrequently, indeed, these agents play as important a part as the streams themselves. Under the conditions now described an elevated plain will in course of time be cut up into more or less numerous segments, the upper surfaces of which will represent the original level of the land; where the interval between two valleys is wide we shall have a broad, flat-topped segment; where the interval is short the segment will be correspondingly restricted in size. In a word, the segments will vary in extent according to the multiplicity and intricacy of the valley-system.

A word now as to the form of the slopes and cliffs bounding the valleys. We are dealing, it will be remembered, with an elevated plain of accumulation. The horizontal strata, we shall suppose, are more or less indurated beds of conglomerate, sandstone, shale, and limestone. All rocks, as we have seen, are traversed by natural division-planes or *joints*, and these in the case of stratified rocks consist of two sets intersecting each other and the planes of bedding at approximately right angles. Horizontal strata are in this way divided up into rudely cuboidal, quadrangular, or rectangular blocks. Joints are, of course, lines of weakness along which, when rocks are undermined,

they tend to give way. Thus when horizontal strata are cut into by rivers and undermined they break off at the joints, and vertical cliffs result. It does not often happen, however, that in a considerable series of strata all the beds are of quite the same character. Frequently some are relatively harder and unyielding, while others are softer and more readily reduced. Let us suppose that the uppermost bed cut into by the river is somewhat hard and difficult to grind through. In time the water saws its way down into the succeeding stratum, which we shall take to be a soft or easily eroded shale. In the overlying hard rock the river has been able to cut merely a narrow steep-sided trench. The shale, however, offers much less resistance to the vertical and lateral action of the water, and is thus rapidly intersected and washed away from underneath the superincumbent harder stratum. The latter, losing its support, then yields along its joint-planes, and a larger or smaller slice is detached from the wall of the cliff and falls in ruins. In this way the cliffs gradually retire as they are undermined—in a word, the ravine is not only deepened but widened.

Much of the rock *débris* dislodged from the cliffs falls into the river, and is gradually broken up and carried away; but some comes to rest at the base, forming a talus, and thus retards the denudation of the shale. To the action of the river we must add that of other epigene agents, such as wind, rain, springs, and frost, under the influence of which the

shale weathers away more rapidly than the overlying rock, and eventually forms a sloping stage upon which the *débris* derived from the receding cliffs continues to accumulate. Meanwhile, however, the river digs down through the shale and encounters, we shall suppose, another thick stratum of hard rock. Lateral erosion by the running water is now reduced to a minimum; slowly the current saws its way down

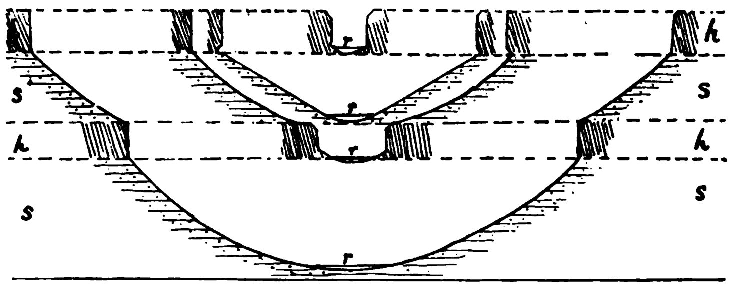

FIG. 10. DIAGRAMMATIC SECTION SHOWING STAGES OF EROSION BY A RIVER CUTTING THROUGH HORIZONTAL STRATA. (After Captain Dutton.)

h, relatively hard rocks; *s*, relatively soft strata; *r r*, river at successive stages as valley is deepened and widened.

vertically, just as it did in the uppermost unyielding bed, until it again reaches a second layer of shale. The undermining action is now repeated, and a second line of rock-wall begins to retreat in the same manner as the first. And so the process goes on with all the succeeding strata through which the river cuts, until it finally attains a minimum gradient and ceases to erode. But note that, while the deepening of the ravine proceeds, the cliffs never cease to retire. Each

individual layer of softer rock continues to waste away more rapidly than the harder bed above it. Thus eventually a river-valley appears bounded, not by vertical cliffs, but rather by a succession of horizontal tiers of precipitous faces, corresponding to the outcrops of the several strata of harder rock—separated the one from the other by the longer or shorter slopes yielded by the shales.

Finally, we may further note that the recession of the cliffs will be much influenced by the rate at which their basal portions are undermined. Each slice removed from a steep rock-face narrows the width and increases the inclination of the sloping stage above. Hence, as Captain Dutton has clearly shown in his admirable description of the Colorado Cañons, the descent of *débris* from each stage is facilitated, while the weathering of the soft rocks and the undermining of the overlying harder beds are accelerated. Thus, curiously enough, as the same author remarks, the state of affairs at the bottom influences the rate of recession at the summit.

When a river has reached its base-level and ceases to erode, the valley-slopes and cliffs, nevertheless, under the influence of weathering, continue to retire. The *débris* showered down from above now tends to accumulate below, and thus affords protection to the rocks against which it is banked. And the talus thus formed continues to rise higher and higher. The exposed strata above, however, having no such protection, weather as before, each rock-tier retreating, but

at a gradually diminishing rate. What form the ground will ultimately assume will largely depend upon climatic conditions. If the climate be moist and frost be active in winter, the sharp edges of the rock-tiers will be bevelled off, and the sloping surfaces will become heavily laden with *débris* and disintegrated rock-material, the further degradation and removal of which will be retarded by the growth of vegetation. Thus, in time, the sharp angles will tend to disappear, and a somewhat undulating slope will replace the more strongly marked features which the same rocks would have yielded under arid conditions.

Let us now recall what was said as to the cutting up of our elevated plain into a multiplicity of flat-topped segments, and we shall see reason to conclude that these segments must be bounded by steep faces, the aspect of which will vary according to the nature of the strata and the character of the climate. If the climate be arid, and the strata consist of alternate hard and soft beds of variable thickness, the bounding walls of the segments may in some places be approximately vertical, or they may show a succession of short cliffs with intermediate sloping stages. If, on the other hand, the climate be moist, those features will be more or less softened and modified. In the former case step-like profiles will abound; in the latter the ground will likewise ascend in stages, but these will be less accentuated, and may even be in large part replaced by continuous slopes. Again, each flat-topped segment of the denuded area, eaten into on all

sides, will continually contract, the bounding cliffs and slopes retiring step by step until they eventually meet atop. The flat summit now disappears, and is replaced by a sharp crest, ridge, peak, or rounded top, as the case may be. Each diminishing segment, in short, ultimately acquires a more or less strongly pronounced pyramidal form. This, however, is not the final stage. Denudation continues—pyramidal hills, dome-shaped heights, and crested ridges gradually crumble down, until at last all abrupt and prominent irregularities of surface disappear, and the once elevated plain returns to its former state, that of a gently undulating or approximately flat stretch of low-lying land. The cycle of erosion is completed.

Thus in the erosion of a plateau of horizontal strata we recognise the following stages :—(1) The excavation of deep trenches by streams and rivers; (2) the gradual sapping and undermining of cliffs, etc., the widening of valleys, and the consequent cutting up of the plateau into a multitude of flat-topped blocks or segments; (3) the progressive contraction of the segments, and their conversion into pyramidal or round-topped hills and crested ridges; and (4) the continued reduction and lowering of the hills and final resolution of the plateau into a plain.

This plain, in the hypothetical case we have been considering, is supposed to be at a level very little above that of the sea. But the minimum level to which a region tends to be reduced need not be at such a low elevation. The streams and rivers dis-

miles long, from 5 to 12 miles wide, and from 5000 to 6000 feet deep." From our present point of view the chief lesson which we derive from a study of the Grand Cañon district is simply this: that horizontally arranged strata tend under the action of epigene agents to form flat-topped mesas and pyramidal hills and mountains. The contours of those prominent features and the detailed sculpturing of cliffs and rock-terraces will depend largely upon the character of the strata out of which the hills and mountains are carved, and also to a great extent upon the climate. In a dry elevated tract like that of the Cañon district the influence exerted by the petrological character of the strata in determining the detailed features of the ground is everywhere conspicuous. In other regions where moister climatic conditions prevail this influence, although never absent, is yet not so strongly marked.

In the foregoing discussion the configuration assumed by horizontal strata has been dealt with in such detail that it is not necessary to cite more than a few other examples to show that wherever the same geological structure occurs denudation has resulted in the production of similar land-forms.

The lonely group of the Faröe Islands, lying about half-way between Scotland and Iceland, are the relics of what at one time must have been a considerable plateau. They extend over an area about seventy miles in length from north to south, and nearly fifty miles in width from east to west. The original

plateau could not have been less than 3500 square miles in extent. But as the islands have everywhere experienced excessive marine erosion, it is certain that the plateau out of which they have been carved formerly occupied a much wider area. The geological structure of the islands is very simple. They are built up of a great succession of basalts with thin intervening layers of tuff (volcanic dust, etc.) arranged in approximately horizontal strata. The islands are for the most part high and steep, many of them being mere mountain-ridges that sink abruptly on one or both sides into the sea. The larger ones show more diversity of surface, but possess very little level land. All have a mountainous character, and, owing to the similarity of the rocks and their arrangement, exhibit little variety of feature. They form as a rule straggling, irregular, flat-topped masses, and sharper ridges, that are notched or broken here and there into a series of isolated peaks and truncated pyramids. Sometimes the mountains rise in gentle acclivities, but more generally they show steep and abrupt slopes, which in several instances have inclinations of 25° to

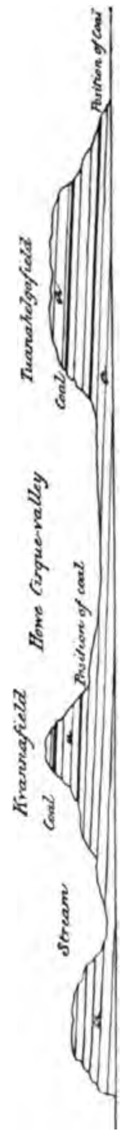

FIG. 11. SECTION ACROSS SUDEROE (FARÖE ISLANDS) ON A TRUE SCALE.
a a, beds of basalt with intervening layers of tuff. Length of section 5 miles.

27° or even 30°. In many places they are yet steeper, their upper portions especially becoming quite precipitous. They everywhere exhibit a well-marked terraced character; precipices and long walls of bare rock rise one above another, like the tiers of some cyclopean masonry, and are separated usually by short intervening slopes, sparsely clothed with grass and moss, or sprinkled with tumbled rock-rubbish. The coasts are usually precipitous, many of the islands having only a few places where a landing can be effected. Not a few are girt by cliffs, ranging in height from 200 or 300 feet up to 1000 feet, and even in some places exceeding 2000 feet. The best-defined valleys are broad in proportion to their length. Followed up from the head of a sea-loch, they rise sometimes with a gentle slope until in the distance of two or three miles they terminate in a broad amphitheatre-like cirque. In many cases, however, they ascend to the water-parting in successive broad steps or terraces. Each terrace is cirque-shaped, and framed in by a wall of rock, the upper surface of which stretches back to form the next cirque-like terrace, and so on in succession until the series abruptly terminates at the base, it may be, of some precipitous mountain. Occasionally the neck between two valleys running in opposite directions is so low and flat that it is with difficulty that the actual water-parting can be fixed. In such cases we have a well-defined hollow, bounded by precipitous, terraced hill-slopes, crossing an island from shore to shore. Were the land to be slightly

depressed such hollows would form sounds separating adjacent islands, while the valleys that head in cirques would form sea-lochs. There can be no doubt, indeed, that the existing fiords of the Faröes simply occupy the lower reaches of land-valleys, and that the sounds separating the various islands from each other in like manner indicate the sites of long hollows of the character just described. In a word, the islands are the relics of a plateau of comparatively recent geological age, for the rocks date no further back than Oligocene times. All the land-features are the result of subaërial erosion guided and determined by the petrological character and horizontal arrangement of the strata. The precipitous cliffs of the coast-line owe their origin, of course, to the undermining action of the sea, the rocks ever and anon giving way along the well-marked vertical joint-planes.

In Great Britain horizontal strata occupy no broad areas. But wherever they put in an appearance they yield the same surface-features. Thus in the north-west Highlands we have the striking pyramidal mountains of Canisp, Suilven, and Coulmore, carved out of horizontal red sandstones of Pre-Cambrian age. In Caithness, again, we have the peaked and truncated pyramids of Morven, Maiden Pap, and Smean, hewn out of approximately horizontal Old Red Sandstone strata. Ingleborough is another good example of a pyramidal mountain having a similar geological structure. Many illustrations are likewise furnished by the horizontal strata of other lands.

Thus pyramidal and more or less abrupt hills, the precipitous sides of which are defined by vertical joints, are common in the horizontally bedded "Quadersandstein" of Saxon Switzerland. So again in the region of the Dolomites, whenever the strata are horizontal the mountains carved out of them tend to assume pyramidal forms. In a word, we may say that all the world over the same geological structure gives rise to the same land-forms.

River-courses hewn in horizontal strata will vary somewhat in form according to the nature of the rocks and the character of the climate. In regions built up of relatively unyielding rocks, or of alternations of these and less resisting beds, the valleys tend to be trench-like, and the mountain-slopes are more or less abrupt. But under the influence of rain, springs, and frost these harsh features are toned down, river-cliffs are benched back, and abrupt acclivities are replaced by gentler slopes. Should the strata consist of soft materials throughout, there will be a general absence of harsh features; round-topped hills and moderate valley-slopes will characterise the land. Nevertheless, whether the strata be "hard" or "soft," thick-bedded or thin-bedded, or show alternations of many different kinds, and whether the climate be arid or humid, equable or the reverse—tropical, temperate, or arctic—the same general type of surface-features can always be recognised.

CHAPTER IV

LAND-FORMS IN REGIONS OF GENTLY INCLINED STRATA

ESCARPMENTS AND DIP-SLOPES—DIP-VALLEYS AND STRIKE-VALLEYS—FORMS ASSUMED BY A PLATEAU OF EROSION—VARIOUS DIRECTIONS OF ESCARPMENTS—SYNCLINAL HILLS AND ANTICLINAL HOLLOWS—ANTICLINAL HILLS.

THE most characteristic land-forms met with in regions where the strata are inclined in some general direction are escarpments and dip-slopes, the former coinciding with the outcrops, and the latter with the inclination or dip of the strata. In such regions some streams and rivers not infrequently flow in the direction of dip, and thus cut across the escarpments, while others may traverse the land along the base of the escarpments.

The origin of these phenomena is not hard to trace. Let us suppose that some wide tract of horizontal strata has been elevated along an axis so as to form a considerable island. If the movement of elevation were slowly effected the sea would doubtless modify the land-surface as it arose, but for simplicity's sake we shall ignore such action, and suppose that the new-born land exists as an elongated island, the sur-

face sloping away at a low angle on either side of a somewhat flattened axis. (Fig. 12.) At first, then, the surface coincides with the underground structure —a dome-shaped land formed of dome-shaped strata. (Fig. 13.) It is obvious that the drainage will be in

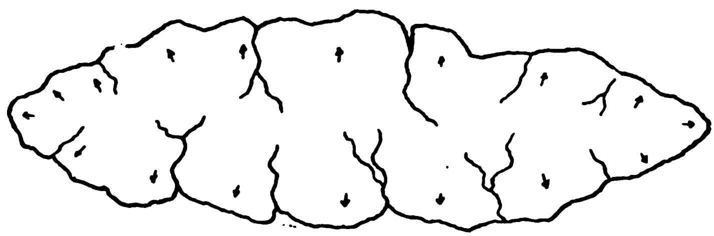

FIG. 12. MAP OF AN ISLAND COMPOSED OF DOME-SHAPED STRATA.
The strata are inclined in the direction of the arrows.

the direction of the dip of the strata—all the main rivers will take the quickest route to the sea. But as we cannot suppose that the surface of the new-made land would be without some irregularities, the streams and rivers would not actually follow straight courses.

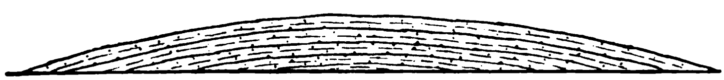

FIG. 13. SECTION THROUGH THE ISLAND SHOWN IN FIG. 12.
Slopes of surface coincide with arrangement of strata.

On the contrary, it could not but happen that one stream would eventually join another, and in this way many might become tributaries of one or more large rivers. Thus we should have certain courses cut in the general direction of the dip, while others joining these would in some places go with the inclination of

the strata, and in other places would traverse that at various angles. The strata consist, we shall suppose, of "hard" and "soft" rocks—limestones, sandstones, shales, etc., and they are well jointed at right angles to the planes of bedding. Thus, while the strata dip seaward, one set of joints is inclined at a high angle in the opposite direction—the other set cutting the strata in the direction of the dip. Now so long as the streams follow the dip it is obvious that they will tend to form trench-like valleys—the rocks will be undermined and give way along vertical joint-planes.

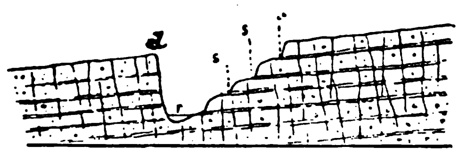

FIG. 14. SECTION OF RIVER-VALLEY.

The valley coincides in direction with the "strike" of the strata, *i. e.*, it trends at right angles to the dip or inclination; *d*, cliff determined by joint; *s s*, springs; *r*, river.

We need not for the present consider the modifications arising from the varying character of the rocks. It is enough to remember that since they yield along the joint-planes, they tend to produce vertical or steeply inclined walls in the same manner as if they were horizontally bedded. But when the course of a stream is more or less at right angles to the dip of the strata, the valley it forms will not have the same trench-like aspect. On one side of such a valley the strata dip away from the stream, and when undermined they yield along the joints which incline inland.

A cliff thus determined is not so liable to be broken down by the action of springs and frost. Underground water tends to move away down the dip-planes, so that no springs come out on the face of the cliff *d* (Fig. 14), which is only renewed from time to time by the undermining action of the river and the consequent collapse of the rock along a steeply inclined joint. On the opposite side of the valley the conditions are different. There the dip is towards the river—a weak structure, for the strata are easily undermined and sapped by springs, coming out along the planes of bedding (*s*, *s*). Hence they readily give way, their *débris* sliding and rolling towards the river. Thus valleys that coincide in direction with the outcrop of the strata will usually show a somewhat precipitous cliff on one side and a more or less gentle slope on the other.

We shall not follow the subsequent history of the erosion of our island in any detail. It is obvious, however, that it must pass through the same stages of erosion as any similar area of horizontally bedded rocks. The rivers and their multitudinous feeders will deepen and widen their valleys until the ground is cut up into a more or less numerous series of segments or blocks. But these will differ in form from those which are carved out of horizontal strata. Instead of flat-topped mesas and buttes and pyramidal-shaped hills, we shall have a series of heights presenting escarpments towards the watershed and long slopes in the opposite direction. (Fig. 15.)

Eventually these will largely disappear, and the whole region will be resolved into a gently undulating plain of erosion.

Now let us suppose that this plain is upheaved and converted into a plateau, the surface of which has a very gentle inclination in the same general direction as the dip. (See Fig. 16, p. 78.) The section at the side of the map shows the geological structure. Here obviously the surface-slope is not so great as the

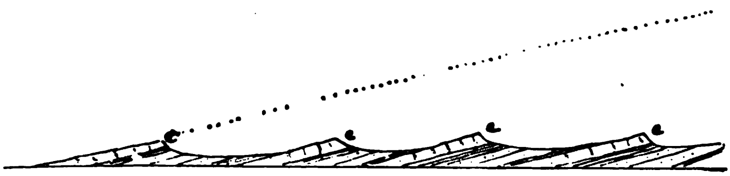

FIG. 15. ENLARGED SECTION OF A PORTION OF THE ISLAND SHOWN IN FIG. 12.

Upper dotted line shows original surface; *e e*, outcrops of "hard" beds forming escarpments.

inclination of the underlying strata; the plateau is therefore a plateau of erosion.

The map represents the course of a main stream with its tributaries. The trend of the drainage will naturally be in the same direction as the dip, and the rivers must therefore traverse the outcrops of the strata. Were the surface of the plateau quite even the waters would, of course, descend by a direct route to the sea. For various reasons, however, it is very unlikely that such should be the case. The strata had no doubt been planed down to a base-level, but some inequalities would still exist—the outcrops of the most durable rocks would here and there project,

however slightly, above the general surface. We may suppose, for example, that the outcrops of the limestones, (*e e*) would form low ridges, rising, it might be, only a few feet or yards. Such slight inequalities would suffice, however, to divert the waters to right or left. The rivers and streams being

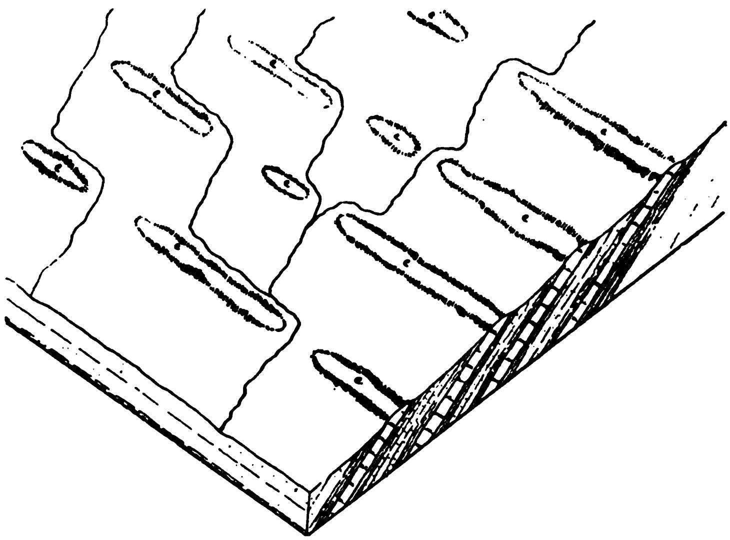

FIG. 16. DIAGRAM MAP OF PLATEAU OF EROSION.

e e, low ridges formed by outcrops of limestone, which are seen in section at the side.

turned in this manner out of their direct course would be compelled to flow along the outcrops until depressions in the ridges allowed them to resume their original direction.

After such a drainage-system had been well established, and the whole surface of the land had been subjected to the action of the various epigene agents

of change for some protracted period of time, the inequalities of surface would become greatly accentuated. The regions occupied by "softer" rocks would be generally lowered, so that the outcrops of the harder beds would stand up more and more prominently. These, however, would not remain unchanged. On the contrary, each bed of hard rock, constantly undermined by the wearing away of the softer underlying strata, would continue to recede at its outcrop. This retreat would be most marked in places where the rivers flowed along the base of the escarpments. But even where rivers were absent the escarpments

FIG. 17. SECTION ACROSS REDUCED PLATEAU OF EROSION.
The upper dotted line represents original surface of plateau as shown in Fig. 16.

would still mark the outcrops of the harder beds. These, no doubt, might not be so prominent as the others, and would not retreat so rapidly, but they would nevertheless come to form striking features in the landscape. In a word, the region would eventually be traversed from left to right by pronounced lines of escarpment rising to many hundreds of feet above the low grounds at their base, and falling away in a long gentle slope in the direction of the dip. When these land-forms were fully developed a section across the reduced plateau would show the structure seen in Fig. 17.

In the case we have been considering the surface of the plateau of erosion is inclined in the same direction as the dip of the strata. Consequently all the escarpments face the water-parting of the region, and all the dip-slopes sink towards the sea. But the surface of such a plateau may be inclined against the direction of the dip; the outcrops, instead of facing the water-parting, may look seawards. Nevertheless, should hard beds be intercalated amongst more yielding strata, escarpments are certain to make their appearance under the influence of denudation, and

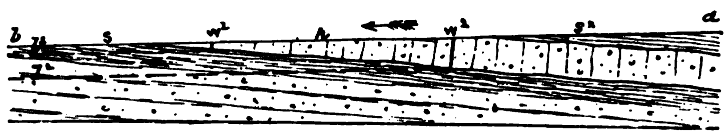

FIG. 18. LONGITUDINAL SECTION OF RIVER-COURSE.

River flowing from *a* to *b*; *h*, outcrop of hard stratum; *s* s^x, shales; w^1, position of waterfall when river-bed has been eroded to the level l^1; w^2, position of waterfall when river-bed has been eroded to the level l^2.

may become quite as prominent as in the case we have just been considering. Nor will the character of river-valleys excavated in the direction of the "strike" of the strata differ; cliffs will tend as before to be developed on one side, and gentle slopes on the other. But in the river-courses that traverse the strike more or less at right angles we shall meet with certain marked contrasts. In regions where the rivers flow in the same direction as the dip of gently inclined strata, waterfalls are not readily formed. When the outcrop of a relatively hard bed is encountered the overlying softer rocks may be rapidly

washed away, and the surface of the underlying hard bed be exposed. At most, however, this simply gives rise to a rapid, which can only approach the character of a waterfall when the strata are inclined at a high angle. But when the strata dip up-stream the conditions are reversed. The outcrop of every hard ledge then gives rise to a cascade, and should the hard rocks attain a considerable thickness a notable waterfall may be produced. In the diagram annexed (Fig. 18) the upper line shows the course of a river (*a–b*) flowing across a series of strata inclined at a low angle up-stream. At *h* we see the outcrop of a bed of hard sandstone or other relatively durable stratum, underlaid and overlaid by soft shales. It is obvious that the river cannot lower the surface of the overlying soft shales (s^x) much below the outcrop of the hard stratum. So long as that endures the beds at s^x are safe. It is otherwise, however, with the underlying shales (*s*). These are more or less rapidly eroded, and in the process of their removal the superjacent hard stratum is undermined, and from time to time gives way along its joint-planes. In this manner the waterfall (w^1) gradually retreats further up the valley (w^2), and a gorge comes into existence.

Thus in the river-courses of a plateau of erosion, composed of gently inclined strata with an up-stream dip, waterfalls tend to be developed at the outcrops of intercalated hard beds. But, as erosion proceeds, these waterfalls retreat up the valley, and so are gradually replaced by gorges.

Now it may be said generally that in all regions composed of gently inclined strata, amongst which relatively hard beds are intercalated, escarpments and dip-slopes are developed by denudation. When the dip of the strata is persistent over a wide extent of country, we shall have more or less prominent escarpments traversing such a region continuously for miles. The escarpments will obviously vary in character with the angle of dip and the nature and thickness of the rocks. If the hard bed or beds be of no great thickness and the dip high, the resulting escarpment and slope will constitute a somewhat narrow ridge; but if the thickness of the hard beds be very considerable and the dip gentle, the escarpment may assume the form of a belt of plateau or a range of high ground, having a more or less diversified surface. England supplies some excellent examples of the kind. The general inclination of the strata between the borders of Wales and the North Sea is easterly, at a low angle; consequently, as we walk in that direction we cross the outcrops of several great geological systems. These are built up of sedimentary rocks, some of which are relatively soft and yielding, such as clay and shale, while others are harder and generally more porous, such as limestone, chalk, etc. Hence in time the latter have come to form a series of more or less prominent escarpments or belts of high ground, separated by broad tracts of gently undulating low ground. Starting from the foot of the Malvern Hills, and proceeding in an easterly

direction, we first traverse low-lying plains of sandstone and argillaceous beds, until on the other side of the Severn we reach the Cotswolds, a belt of high ground over 1000 feet in height, and reaching in places a width of 30 miles. The rocks of which these hills are composed consist principally of limestones, which, as they dip gently eastwards, are succeeded by a series of argillaceous beds, forming again a region of undulating plains. Traversing these plains in the direction of dip, we eventually encounter another broad belt of high ground—the escarpment of the Chalk. This escarpment in its turn is succeeded by a low-lying region composed chiefly of relatively soft argillaceous beds and other non-indurated strata.

A glance at any geological map of the country will show that all the prominent hills and high grounds of central and south-eastern England are developed along the outcrops of the Jurassic limestones and the Chalk, and thus have a general northerly or north-easterly trend. We cannot doubt that the present irregularities of the surface are the result of long-continued epigene action, guided by the character of the rocks and the geological structure of the ground. The yielding strata have been worn away more rapidly than the harder rocks, while the escarpments formed by the latter have slowly retreated as denudation proceeded. This is sufficiently evidenced by the fact that detached outliers of the more durable beds are met with lying beyond the general outcrop of the series. Thus in Fig. 19 the outliers of Chalk (1, 2)

were obviously at one time connected with the main mass *C*—the dotted line representing the conditions of surface that formerly obtained. In a word, the detached masses have been left behind during the retreat of the escarpment to its present position. The course of the River Thames, whose head-waters rise on the east side of the Cotswold Hills, was doubtless deter-

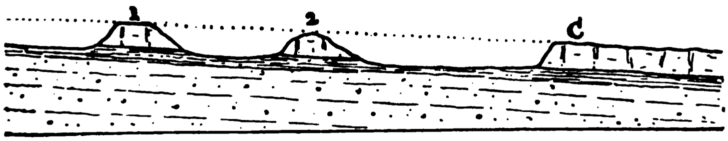

FIG. 19. SECTION OF ESCARPMENTS AND OUTLIERS.

mined by the inclination of the original surface of the ground. It will be observed that, like the streams represented in Fig. 16, this river flows across the outcrops of the Jurassic and Cretaceous strata, cutting through the Chalk escarpment between Wallingford and Reading.

Although wide regions may be built up of strata

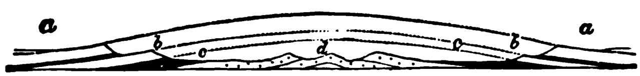

FIG. 20. SECTION ACROSS THE WEALDEN AREA. (Ramsay.)
a, Upper Cretaceous strata ; *b*, Lower Greensand, etc.; *c*, Weald clay ; *d*, Hastings sands, etc.

dipping continuously in one direction, yet it is more usual to find the direction of dip changing. Such changes may occur at wide intervals, or they may succeed each other within narrower limits. Sometimes we may have the beds of a broad area arranged in

one single anticline or syncline as the case may be. In other places the undulations of the strata may be numerous. Many examples of such structures might be cited from the rocks of Great Britain. Restricting attention for the present to gently inclined and undulating strata, we encounter a fine illustration of a broad anticline in the Chalk Downs and the Weald. (Fig. 20.) The latter might be described as a wide amphitheatre, open to the sea on the east, but surrounded in all other directions by bold bluff-like hills. Here the configuration has had precisely the same origin as the escarpments of the Midlands. The North and South Downs coincide with the outcrops of the Chalk, while the enclosed low grounds have been excavated out of underlying argillaceous and other unconsolidated strata. The Chalk, one cannot doubt, originally extended over the whole of the Wealden area, as shown by the dotted lines in Fig. 20. That high ground formerly existed within this area is clearly indicated by the fact that the escarpment of the Downs has been sawn across by streams flowing out from the heart of the Weald. Obviously when these streams first began to flow, the water-parting in the axis of the Weald must have been at a higher level than the present summit of the Downs. The whole surface has been lowered by epigene action—the less readily reduced rocks and rock-structures forming as usual the most prominent features in the landscape.

The denudation of a broad anticline composed of

harder rocks intercalated among a series of more yielding strata results, as in the Wealden area, in the formation of lines of escarpment facing each other. In the case of a denuded syncline of similar strata escarpments are likewise developed, but their faces are now turned in opposite directions. Fig. 21 shows the geological structure of a portion of Ayrshire. Here we have a series of hard volcanic rocks (v^2), old lavas, in fact, intercalated between underlying and overlying sedimentary strata—chiefly sandstones and shales. The result is the same as in all the cases already considered—the more durable rocks crop out

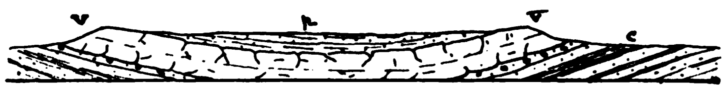

FIG. 21. SECTION ACROSS PERMIAN VOLCANIC BASIN, AYRSHIRE.
c, Carboniferous strata; *v*, volcanic rocks; *p*, Permian sandstones.

strongly and form escarpments, but these look away from and not towards each other.

In regions which have experienced much denudation, gently inclined strata, when arranged in a series of anticlines and synclines, not infrequently give rise to an undulating surface. But this surface does not coincide with the deformations of the rocks below. In point of fact, anticlines are not infrequently represented at the surface by depressions, and synclines by elevations. These phenomena are best developed when beds or masses of durable nature are intercalated in a series of more yielding rocks. In the accom-

panying section (Fig. 22) it will be observed that synclines coincide with hills, and anticlines with valleys. This configuration has been determined by the geological structure. In each hill we have practically two escarpments placed back to back. The beds *h h* are relatively harder than others in the series. Had no such beds occurred the synclines would probably not have been so strongly emphasised by elevations. But the presence of one or more hard beds in series of undulating and relatively soft strata does not necessarily give rise to synclinal hills. The hard beds in such a series would no doubt in time crop out at the surface

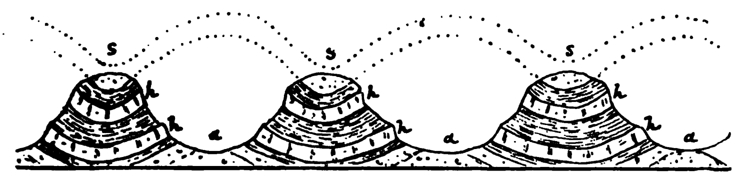

FIG. 22. SYNCLINAL HILLS AND ANTICLINAL VALLEYS.
s s, synclines; *a a*, anticlines; *h h*, relatively hard beds.

and project above the base-level of the district; but if in the synclinal troughs they descended below that level, they could have no influence upon the surface. Thus in the section (Fig. 23) a relatively hard bed crops out and forms escarpments at *e e*, but it descends below the base-level, *b b*, in the two synclinal troughs (s^1 s^2), which remain unaffected by it. In the third trough (s^3), however, it remains above the base-level, protecting the underlying softer beds, and thus forming a hill.

When a series of undulating strata contains no intercalated hard beds, but is of much the same consistency throughout, the synclines still offer the stoutest resistance to denudation, anticlines being relatively weak structures. In the former the strata are not liable to be undermined and displaced by the

FIG. 23. ESCARPMENT HILLS AND SYNCLINAL HILL.
$e\ e$, hard bed; $s^1\ s^2\ s^3$, synclinal troughs; $b\ b$, base-level.

action of springs. In the latter, however, the strata hang away from the axis, and water percolating through them, and coming out along the bedding-planes, tends to their demolition. But this is a matter which will be considered more fully when we come

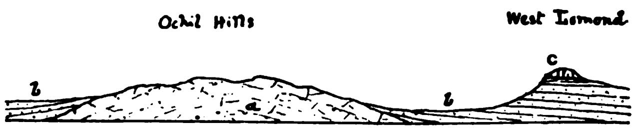

FIG. 24. SECTION ACROSS WEST LOMOND HILL AND THE OCHILS.
a, igneous rocks; b, red sandstones, etc; c, basalt.

to consider the surface-forms yielded by steeply inclined and highly folded strata.

In regions long exposed to denudation all weakly built hills tend to disappear. Hence in such countries anticlinal hills are of very rare occurrence. Now and again they do occur, but only when they happen to be composed of more durable rocks than those which

repose upon their flanks. The Ochils of Kinross afford us a good example. (Fig. 24.) Here we have an underlying series of hard igneous rocks, *a*, folded along an axis from which they dip away on both sides below overlying sheets of red sandstone. These red sandstones almost certainly at one time extended across the anticline, which has thus been

FIG. 25. SYNCLINAL VALLEY WEST OF GREEN RIVER. (Powell.)

much denuded. But, owing to the greater durability of the igneous rocks, the anticline, of which they form the axis, continues to show as a prominent elevation.

Hitherto we have been considering the surface-forms assumed by gently folded strata in regions

which have been subjected for a more or less prolonged period to subaërial denudation. In areas where deformation of the strata has been effected within geologically recent times, not infrequently some coincidence may be observed between the undulations at the surface and the underground struct-

FIG. 26. ANTICLINAL RIDGE, GREEN RIVER PLAINS. (Powell.)

ure. The Colorado district we have described as a region of practically horizontal strata. Here and there, however, the rocks are more or less folded, and when such is the case they often give rise to corresponding folds at the surface. In the region traversed by Green River, for example, the horizontal strata occa-

sionally show anticlines and synclines, as in the following sketches from Major Powell's description of the Cañon country, where the synclinally arranged beds in Fig. 25 form a valley, while the anticlinal strata in Fig. 26 appear as a swelling ridge.

Such coincidence of underground structure and superficial configuration, however, is not always to be traced even in so young a land as the Cañon district, while, as already remarked, it is of very uncommon occurrence in lands of high geological antiquity.

CHAPTER V

LAND-FORMS IN REGIONS OF HIGHLY FOLDED AND DISTURBED STRATA

TYPICAL ROCK-STRUCTURES IN REGIONS OF MOUNTAIN-UPLIFT—GENERAL STRUCTURE OF MOUNTAINS OF UPHEAVAL—PRIMEVAL COINCIDENCE OF UNDERGROUND STRUCTURE AND EXTERNAL CONFIGURATION—RELATIVELY WEAK AND STRONG STRUCTURES—STAGES IN THE EROSION OF A MOUNTAIN-CHAIN—FORMS ASSUMED UNDER DENUDATION—ULTIMATE FATE OF MOUNTAIN-CHAINS.

WE have now to study the various land-forms that characterise regions where highly folded strata occur. Deformation of the crust has taken place in all ages of the world's history. In some countries rock-plication and folding date back to the earliest period of which geologists have any certain knowledge. In other places the deformations belong to relatively recent times. Again, we find evidence to show that certain areas have experienced such changes at many successive periods. As might have been expected, the oldest rock-folds have suffered excessive erosion, while the youngest have experienced less. We are thus able to study in different countries the successive phases through which a region of highly

disturbed strata must necessarily pass. We see it in its youth in such mountains as the Alps, the Himalayas, the Cordilleras, and in its old age in the Appalachians and the mountains of Scandinavia and Britain.

Let us now briefly consider some of the typical kinds of structure presented by the more steeply inclined strata. In regions of moderately inclined rocks the folds, as we have seen, are symmetrical anticlines and synclines, the axes of which are vertical, the beds

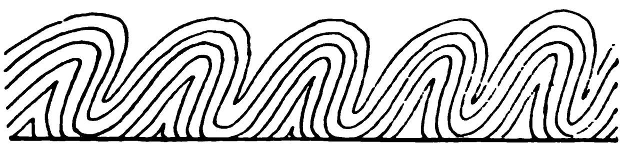

FIG. 27. ISOCLINAL FOLDS.
Axes moderately inclined from the vertical.

dipping away from or towards the axes at approximately equal angles. (See Fig. 22, p. 87.) Folds of this kind, however, are not restricted to areas of moderately inclined strata; they are met with also in regions where the rocks as a rule dip steeply. But in such regions the anticlines and synclines are usually more or less unsymmetrical—their axes are inclined. In Fig. 27 we have represented a series of moderately inclined folds. In Fig. 28 the inclination of the axes is still greater. As the folds in these two diagrams all lean in one direction, they are said to be *isoclinal*. Very frequently the inclination of the axes increases to such a degree that one fold may come to lie almost hori-

zontally upon another, as in Fig. 29. But when the axes are so highly inclined as that the folds usually

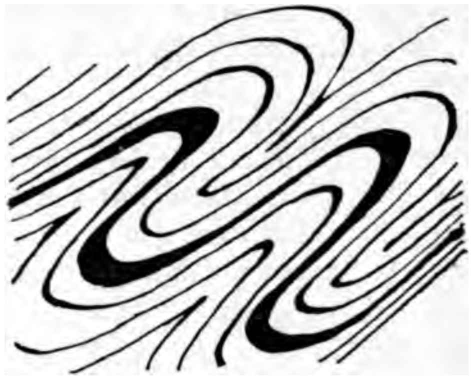

FIG. 28. ISOCLINAL FOLDS.
Axes much inclined.

tend to become disrupted. All folds are the result of horizontal push or tangential pressure, and when this is very great they may yield by shearing, and

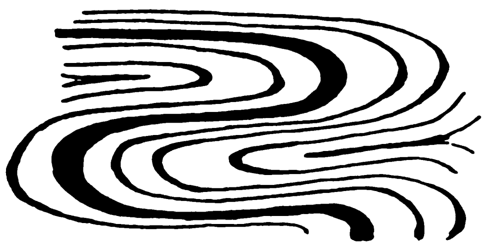

FIG. 29. ISOCLINAL FOLDS.
Axes horizontal = overfolds.

one limb be thrust forward over the other, producing what is known as a *reversed fault*. (Figs. 30, 31.)

So overpowering has been the horizontal movement in some cases that masses of rock thousands of

feet in thickness have been buckled up and sheared, or, simply yielding to pressure, have sheared without folding, and been thrust forward for miles along a

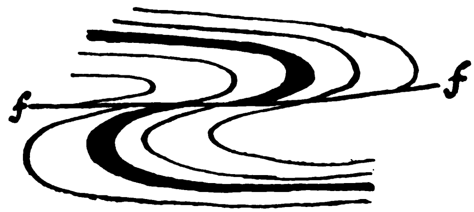

FIG. 30. OVERFOLD PASSING INTO REVERSED FAULT OR OVERTHRUST.

gently inclined or even an approximately horizontal plane. These great reversed faults are termed *over-thrusts* or *thrust-planes.* Sometimes such thrust-

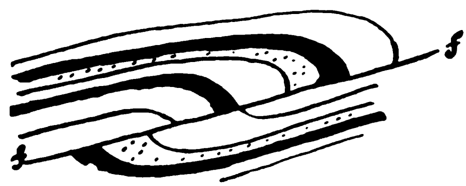

FIG. 31. REVERSED FAULT.

planes occur singly (Figs. 32, 33), at other times the rocks have yielded again and again, great sheets having been sliced off successively and driven forward one upon the other. (Fig. 34.)

Another structure encountered in regions of much

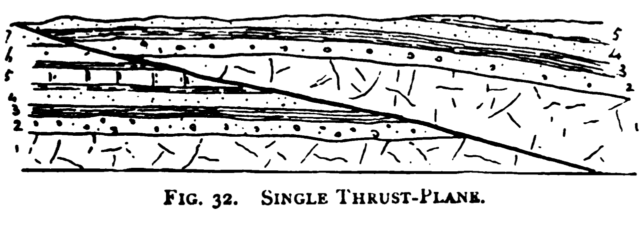

FIG. 32. SINGLE THRUST-PLANE.

disturbed strata is the *synclinal double-fold*, shown in the annexed diagram. (Fig. 35.) In this case two anticlinal folds approach each other from different directions, the synclinal depression between the approximating anticlines being occupied by highly convoluted strata.

The converse of this structure is the *anticlinal double-fold* as shown in Fig. 36. Here two synclinal folds

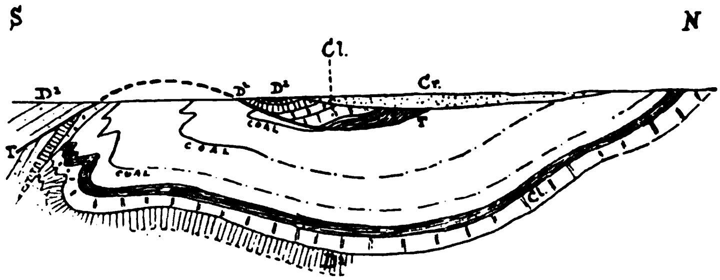

FIG. 33. SECTION ACROSS COAL-BASIN OF MONS. (M. Bertrand.)

D^1 D^2, Lower and Upper Devonian; *Cl*, Carboniferous Limestone; *Cr*, Cretaceous; *T*, Overfold and thrust-plane. Devonian and Carboniferous strata turned upside down above the thrust-plane.

approach each other, while in the intervening space the strata are arched into a great anticline. The beds within the anticline, it will be observed, are much compressed below, while they open out above. This is known as *fan-shaped structure*.

Reverse faults and thrust-planes have been referred to, but it must be noted that normal faults also now and again occur in complicated regions. The former, as we have seen, are the result of horizontal, the latter of vertical movements of the crust. Reversed faults, therefore, are almost entirely restricted to regions

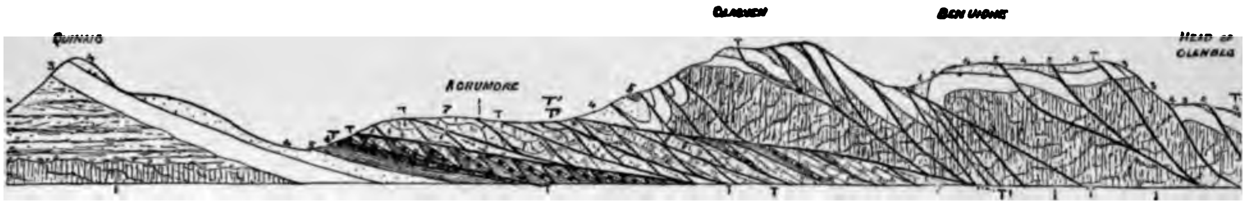

FIG. 34. SECTION FROM QUINAIG TO HEAD OF GLENBEG. (*Geol. Survey.*)

1, Lewisian gneiss; *2*, Torridon sandstones (Pre-Cambrian); *3*, *4*, lower and upper quartzite; *5*, fucoid beds; *6*, serpulite grit; *7*, limestone; (*3* to *7* = Cambrian); *T T*, thrust-planes.

FIG. 35. SYNCLINAL DOUBLE-FOLD.

where the rocks are more or less steeply inclined and contorted. Normal faults, on the other hand, occur under all conditions of rock-structure—traversing alike horizontally arranged strata and inclined and folded beds of every kind.

So much, then, for the general types of structure met with among highly folded strata. So far as our present knowledge goes, complex folding, such as is

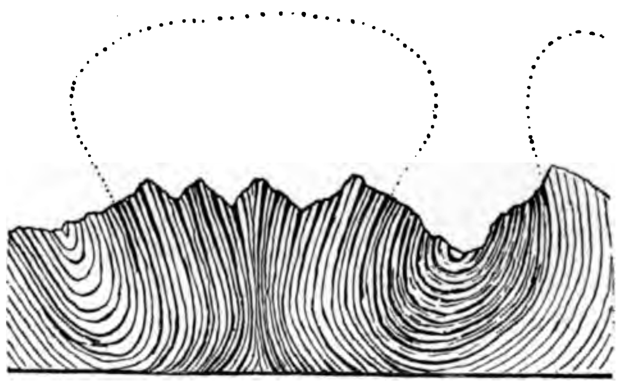

FIG. 36. ANTICLINAL DOUBLE-FOLD.

seen in true mountains of uplift, has resulted from horizontal movement in one direction. This is shown by the manner in which most of the more closely compressed and steeper folds of a mountain-chain tend to lean over one way. Under the influence of an irresistible horizontal thrust the strata find relief by folding, and the crust bulges upwards, the flexured rocks naturally bending over in the direction of least resistance. The resulting structure may be shown diagrammatically as in Fig. 37. In this diagram only

folds are represented; in many cases, however, the rocks are not merely flexed, folded, and contorted, but dislocated and displaced. Frequently, indeed, they have yielded to the intense pressure by shearing, and slice after slice, hundreds or even thousands of feet in thickness, has been pushed forward and piled one on top of the other. Although the closer folds tend as a rule to lean over in the direction of crustal movement, yet occasionally they are inclined in the opposite direction, thus giving rise to the well-known

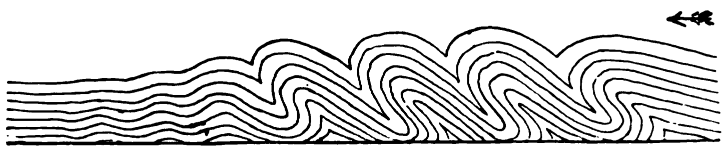

FIG 37. DIAGRAM OF MOUNTAIN FLEXURES.
The arrow shows the direction of thrust.

fan-structure seen in the anticlinal double-fold, Fig. 36. Now and again, too, the folds may open out, and so form symmetrical flexures with vertical axes, or normal anticlines and synclines. The cause of such variations in the folding of the strata is an interesting question, but does not concern us here.

When a tract of highly disturbed rocks has been exposed to erosion for a very prolonged period, it is usually hopeless to attempt to reconstruct the original configuration of the ground, save in a very general way. The primeval land-forms that may have resulted from crustal deformation have been entirely remodelled or removed by denudation. But there

are many regions where similar extensive deformation has taken place at a relatively recent geological date, and where, therefore, time has not sufficed for the obliteration of all surface-features due to crustal disturbance. In the younger mountain-chains of the world, underground structure and orographical features to a certain extent coincide. The study of these mountains, therefore, enables us to realise the conditions that formerly obtained in tracts of highly complicated structure, from which, under long-continued erosion, all trace of the original configuration of the ground has vanished. Not only so, but the havoc wrought by epigene action upon even the youngest of our mountains shows us how and by what means the complicated mountain-chains of earlier days have gradually been reduced. For, just as lands built up of horizontal and gently inclined strata have experienced various degrees of erosion, thus enabling us to trace the successive stages through which such lands must pass, so regions of highly complex structure present us with various phases of denudation. And thus, by comparing one tract with another, we may spell out the whole story; and in the degraded relics of former mountain-systems we read the fate that must eventually overtake the proudest elevations of the present.

The study of the land-forms assumed by highly flexured strata should naturally begin with the examination of some young mountain-chain. But even the youngest of such mountains has already under-

gone much erosion, and its structure is often extremely complicated. To examine any one system in detail, and to follow the whole process of its denudation, would be a laborious work, far beyond the limits of our present inquiry. All that we desire is to ascertain if we can how far geological structure and orographical configuration coincide during the period of a mountain's infancy and early youth, and by what means its original form becomes modified and eventually remodelled. For this purpose we may profitably begin our study by considering first some hypothetical case. We shall suppose, then, that under tangential pressure the horizontal strata of some region have bulged up and become folded along a given line or zone. Under such conditions great faults and thrust-planes would be likely enough to occur; but for the sake of simplicity we shall ignore these, and fix our attention only on the flexing and folding. We shall suppose further that our mountain-chain is the result of one prolonged continuous earth-movement. How, then, will the elevation of the strata affect the surface? Will the complex folding of the rocks give rise to similar intricate deformations of the surface? This does not necessarily follow, for, were the movement of elevation very slow and protracted, the gradually rising surface might be so continually reduced by denudation that underground structure and external form would rarely or never correspond. But, on the other hand, were the rate of elevation in excess of the rate of erosion, the larger folds of the strata

might be expected to give rise to similar undulations at the surface. It is very doubtful, however, whether the latter would ever be as strongly pronounced as the former; for at great depths the folds would be pressed closely together, while they would naturally tend to open out upwards into broader undulations. Hence, deeply buried rock-masses might be intensely flexed and folded, while the surface might show only a more or less pronounced bulging. The infant mountain might appear as merely one single long swell or undulation, with smooth slopes, declining at no great angle to the low grounds. Or there might be a series of two or more such undulations. The study of existing mountain-chains, however, leads to the belief that in some cases at least very considerable deformation of the surface has accompanied mountain-making, all the larger folds of the strata being probably at first represented above ground by corresponding ridges and depressions.

We do not know whether the elevation of a mountain-chain was ever suddenly effected. So far as we can judge from the evidence supplied by geological structure, it would seem as if the horizontal movements of the crust had been gradual and protracted, and often interrupted by long pauses. There is little reason to doubt, however, that during the growth of a mountain-chain sudden snapping of rocks under pressure must have occurred frequently enough, and that earthquakes of greater or less intensity must have accompanied the upheaval. If such has been

the case, it would follow that the surface might be very considerably affected—rocks might be shattered and weakly constructed ridges shaken down—so that the anticlinal ridges of a mountain-chain might well have presented, even in the days of its infancy, a broken and ruptured surface.

But, to return to our hypothetical mountain-chain, we shall suppose this consists of a series of parallel ridges which attain their greatest elevation along a line or axis not far removed from the thrust-side of the chain. From this axis the ridges decline gradually in importance in the direction of earth-movement, and eventually die out in a series of gentle undulations. Each of the ridges, we shall suppose, coincides with an anticline, and each of the intervening hollows with a syncline. In a word, we shall take the surface to be a more or less exact expression of the geological structure, the undulations of the ground, however, being less pronounced than those of the strata at considerable depths. The diagram (Fig. 37, page 99), will represent a section across such a chain. It will be observed that all faults and possible intrusions of igneous rock are neglected.

In any series of stratified rocks some are sure to be more porous than others, while all will be traversed by joints or cracks approximately at right angles to the bedding-places. This, then, we shall take to be the case with the rocks of which our young mountain-chain is composed; and we shall suppose that the parallel ridges extend in a linear direction for many

miles, gradually declining in elevation towards both ends of the chain. With these conditions of surface, it is obvious that drainage will take place in the direction of the great longitudinal valleys or synclinal troughs, while a set of transverse streams will flow down the slopes of the anticlinal ridges. Many of these will thus become tributary to the rivers making their way along the axial hollows. All the rivers in course of time must cut into the rocks, but it is obvious that the transverse streams will be of a torrential character, and will tend therefore to carve out narrower, deeper, and straighter channels than the larger rivers can excavate in the less inclined, broad axial depressions. Immense quantities of rock-material will be swept down from the anticlinal ridges to accumulate in heaps and sheets in the synclinal troughs, or to be swept away more readily, according as the gradients of the latter are gentle or steep. Erosion, in short, will be carried on most actively upon the anticlinal mountains. This would naturally follow, whatever the character of the geological structure might be, for the erosive action of running water increases with the gradient.

But in all cases denudation is hastened or retarded according as the rock-structure is weak or strong. If, therefore, the mountains of our hypothetical chain be more weakly built than the parallel synclinal troughs, the former will tend to be reduced more rapidly than the latter. This can be shown diagrammatically as in Fig. 38, p. 105. Here we have a section across two

anticlinal mountains and a synclinal valley. The strata consist of a series of more or less porous sandstones separated by intervening layers of impermeable clay-rocks. Moreover, they are jointed, and the joints traversing the anticlines tend to open out upwards, while the reverse is the case with those cutting the synclines. Some of these joints may be shrinkage-cracks which came into existence during the slow consolidation of the strata, perhaps long before the latter were flexed and folded. But a large proportion no doubt would be produced while the rocks were being bent and doubled up. In whatever way formed, joints are readily permeated by meteoric water, which finds its way down from the surface and soaks into

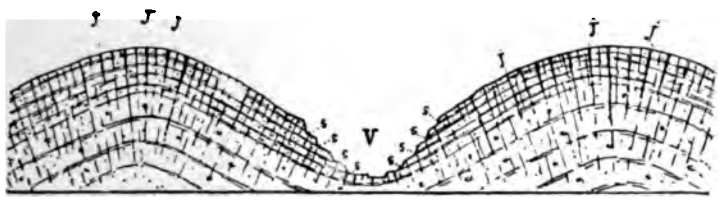

FIG 38. DIAGRAM OF ANTICLINAL MOUNTAINS
Pervious strata (stippled) and impervious layers (thin lines); *j j*, joints, cutting strata at right angles; *v*, valley; *s s*, springs coming out at junction of pervious and impervious beds.

the porous strata below. Constantly augmented from above, the water thus imbibed is forced to percolate through the porous beds in the direction of the dip. Hence wherever these beds are truncated (as in the valley) the water comes out at the surface as natural springs. Thus in the illustration springs appear at *s s*, where permeable sandstones are underlaid by im-

permeable clay-rocks. The effect of these springs is not hard to understand. They tend to undermine the sandstones, and as the dip of the strata is towards the valley, rock-falls and landslips must continue to take place until the anticline is reduced. Anticlinal mountains separated by a synclinal trough are thus in a state of unstable equilibrium. Sapped and undermined by rain, frost, and springs, their existence

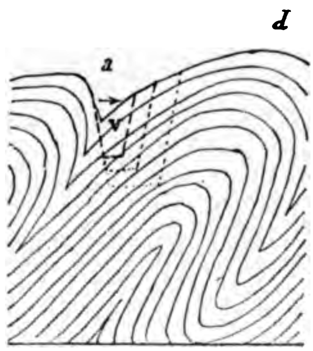

FIG 39. SYNCLINAL VALLEY SHIFTING TOWARDS ANTICLINAL AXIS.
a, synclinal valley ; *d*, anticline ; *v*, valley, gradually widened in the direction of the arrow.

cannot be prolonged. On the other hand, the strata in the synclinal trough, although consisting of the same materials, will be relatively more durable. Their arrangement favours their preservation ; they are not sapped and undermined as in an anticline, but are reduced chiefly by the vertical erosion of the rivers that traverse them.

The anticlines of our mountain-chain are thus not only deeply incised by transverse streams and torrents,

but they are liable all along their flanks to the undermining action of the longitudinal rivers and their allies, —rain, frost, and springs. Quite undisturbed by earthquakes, their destruction by epigene action is, nevertheless, assured. But if the young mountain-chain be liable, as all such mountains are, to earthquake-shocks, the demolition of the already weakened anticlines will often be greatly accelerated.

Unsymmetrical anticlines are not less liable to destruction than those we have just been considering. Indeed, their arrangement must lead sometimes to the gradual shifting of a longitudinal river from a synclinal to an anticlinal axis. Thus a river occupying the syncline *a* (Fig 39), and eventually cutting more or less deeply into the underlying strata, will tend to work its way towards the axis of the anticline *d*. For it will be observed that the beds of that anticline dip into the valley, while those on the other side dip away from it. The latter, therefore, is a strong structure, and the valley-cliffs will recede relatively slowly in that direction, while rock-falls and landslips will prevail on the side of *d*. The valley, therefore, will be widened most readily towards *d*; and, the like conditions obtaining in all the longitudinal valleys of a chain, the time will come when every similarly constructed anticlinal ridge may be reduced.

Many other modifications of the drainage of a mountain-chain will be brought about by the action of the streams and rivers. Thus a transverse stream, which as a rule works more energetically than a longi-

tudinal river, may now and again succeed in cutting its way back across an anticline so as to tap some adjacent synclinal trough. If the bottom of this trough should chance to be at a higher level than that of the hollow into which the transverse stream makes its way, the river of the invaded syncline may be captured by the stream. Thus we should have the phenomenon of a longitudinal river changing its course and becoming transverse.

The chief point, however, which we have at present to bear in mind is simply this: that anticlinal structures are weak and tend to be reduced; while synclinal arrangements are relatively strong, and consequently more persistent. We should expect to find, therefore, in all mountains of upheaval, exposed for any time to denudation, that synclinally arranged strata will not infrequently appear in a tolerable state of preservation; while anticlinal beds will often be deeply eroded. Let us, then, turn our attention to the structures met with in such a region as the Alps, and see how far they bear out these elementary conclusions.

That great chain is a typical example of what are known as mountains of elevation. It consists essentially of a succession of anticlines and synclines, chiefly unsymmetrical. The strata are not only folded and often exceedingly contorted, but the structure is still further complicated by vast thrust-planes and normal faults. Moreover, the chain is the result, not of one, but of many successive earth-movements. But the chief movement—that, namely, to which the

mountains owe most of their present elevation—took place at a relatively late geological period. Many of the folded and fractured rocks, indeed, are of no greater antiquity than the soft clays and sands over which London is built. And yet, although the chain belongs to so late a date, its rocks everywhere bear witness to great erosion. Enormous masses of material have been gradually removed, and the original surface, due to folding and displacement, has been more or less profoundly modified.

The sketch-section across the Swiss Alps (Fig. 40, p. 110) gives the general arrangement of the strata, and enables us in some faint measure to appreciate the degree of denudation which has already been experienced by these relatively young mountains. Grant, if you will, that the folding of the strata may have resulted in a kind of chaos at the surface—that the ground along the axes of anticlinal arches may have been ruptured, and the rocks everywhere tumbled in confusion—yet we have still to account for the wholesale removal of the abundant *débris*—the shattered reefs and dislodged mountain-masses. We cannot, in short, escape from the conclusion that an enormous amount of denudation has taken place. So profoundly has the original configuration been modified, that it is only when the mountains are viewed in the broadest way that any coincidence between underground structure and surface-features can be observed. Even where anticlines still form hills and mountains it is obvious that they have yet

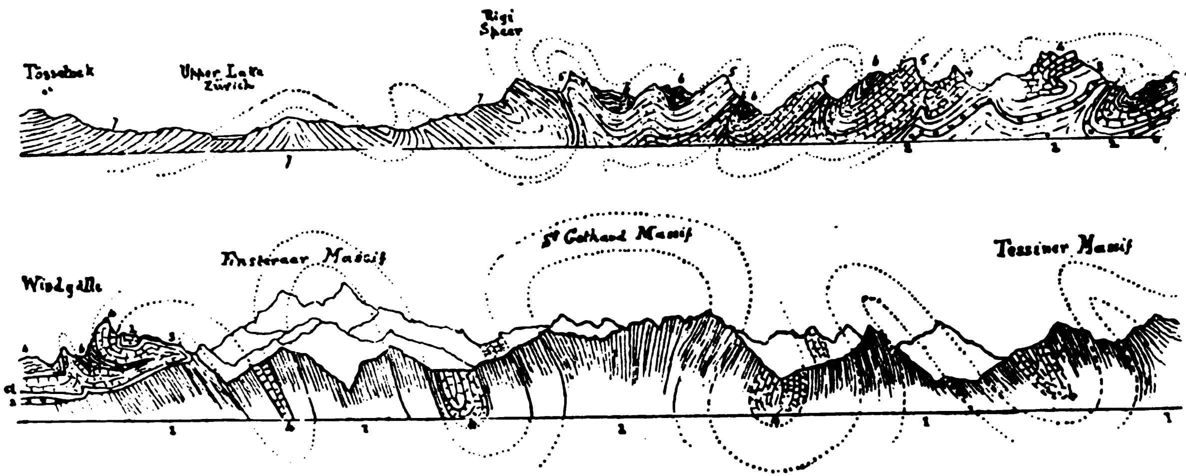

FIG. 40. SECTION ACROSS THE SWISS ALPS (A. Heim).

1, Crystalline schists and Palæozoic strata; *2*, Triassic; *3*, *4*, Jurassic; *5*, Cretaceous; *6*, Eocene; *7*, Miocene.

suffered extensive degradation. (See Fig. 41.) Not infrequently, indeed, they are more or less deeply

FIG. 41. SUMMIT OF SANTIS, EAST SIDE (A. Heim).
Anticlinal mountain.

trenched—valleys running along their axes, an appearance well shown in Fig. 42. Synclinal hollows

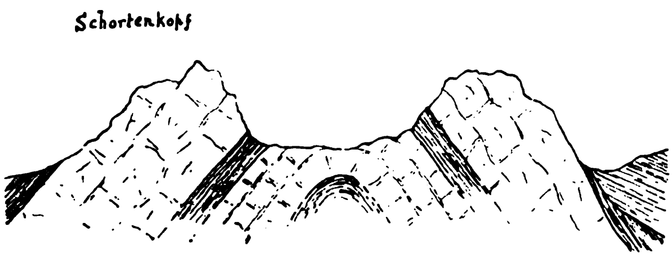

FIG. 42. SECTION ACROSS THE SCHORTENKOPF, BAVARIAN ALPS (E. Fraas).
Anticlinal valley in calcareous rocks and shales (Triassic.)

now and again coincide with depressions at the surface, as in Fig. 43; but they just as often, or even

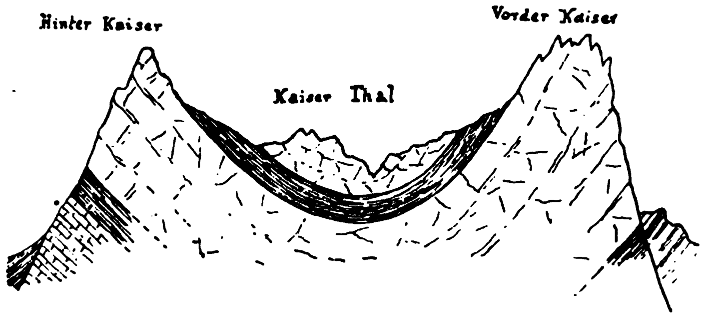

FIG. 43. SECTION ACROSS THE KAISERGEBIRGE, EASTERN ALPS (E. Fraas).
Synclinal valley in calcareous rocks and shales (Triassic).

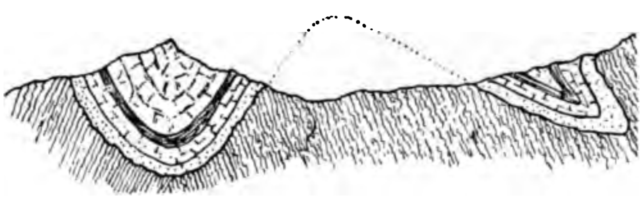

FIG. 44. SECTION ACROSS THE VAL D'UINA (Gümbel).
Triassic strata resting on crystalline schists.

FIG. 45. SICHELKAMM OF WALLENSTADT (Heim).
Sickie-shaped overfold.

more frequently, form elevations, as in Figs. 44, 45. In every case, however, the evidence of denudation

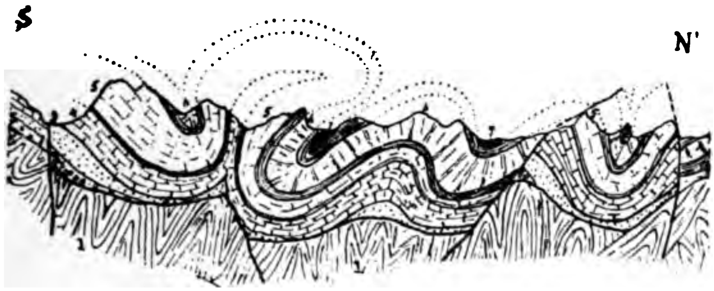

FIG. 46. SECTION ACROSS THE NORTHERN LIMESTONE ALPS (E. Fraas).
1, Crystalline schists; *2*, Permian; *3*, Bunter; *4*, Muschelkalk; *5*, Limestone (Wettersteinkalk); *6*, Dolomite; *7*, Jurassic and Cretaceous.

is conspicuous. Nor is this less clearly seen in the more complicated structures of the Alps. In the fol-

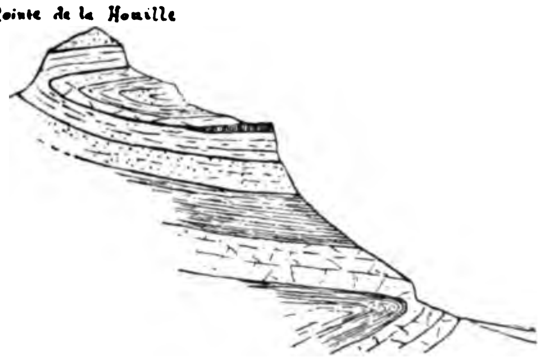

FIG. 47. SECTION ACROSS THE DIABLERETS (Renevier).
Tertiary strata showing a succession of overfolds.

lowing section, for example (Fig. 46), we have a series of various calcareous strata and underlying schists compressed into folds and dislocated, the tops of the

anticlines having in each case been removed. Take again the section of the Diablerets (Fig. 47), in which the Tertiary strata are doubled back upon themselves

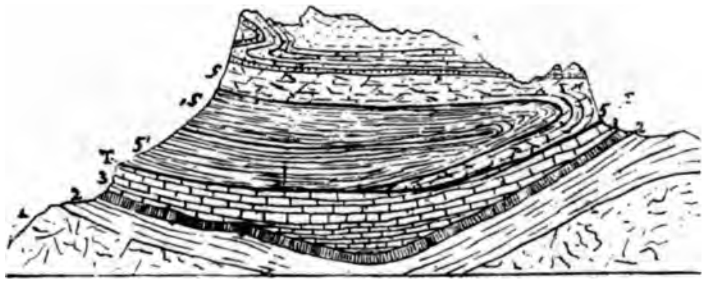

FIG. 48. SECTION ACROSS DENT DE MORCLES (Renevier).

1, Schistose rocks, etc.; *2*, Carboniferous strata; *3*. Jurassic strata; *4*, Cretaceous strata; *5*, Tertiary strata; *4*, *5*, $_15$, Cretaceous and Tertiary rocks inverted; *T*, thrust-plane.

in a series of sharp overturned flexures. A similar, but somewhat more complicated, structure appears in the Dent de Morcles (Fig. 48), where the remarkable

FIG. 49. INVERSION AND OVERTHRUST IN THE MOUNTAINS SOUTH OF THE LAKE OF WALLENSTADT (E. Fraas, after A. Heim).

s, Schistose rocks; *p*, Permian; *wj*, *bj*, Jurassic; *c*, Cretaceous; *e*, Eocene. The Permian strata (*p*) are turned upside-down and thrust upward over the contorted Eocene (*e*).

overturn flexure rests upon a thrust-plane. Here, again, the strata, it will be observed, are doubled back upon themselves, or turned upside-down. Obviously these mountains are monuments of excessive erosion.

Similar evidence of vast rock-removal is furnished by the remarkable double-folds and overthrusts in the mountains of the Cantons Glarus and St. Gall, as described by Heim and others (See Fig. 49.)

Similar conclusions may be drawn from the appearances presented by every kind of rock-structure throughout the whole extent of the Alps.

In the Jura mountains the rock-foldings are sometimes symmetrical, and anticlines and synclines now and again coincide with hills and valleys respectively, as in Fig. 50.

It will be observed, however, that the synclinal strata have suffered less erosion than the intervening

FIG. 50. SYMMETRICAL FLEXURES OF THE JURA MOUNTAINS.

Anticlinal mountains and synclinal valleys.

anticlinal strata. In the western part of the same range of mountains the folds are less symmetrical, but they yield the same evidence of denudation. The accompanying section (Fig. 51, p. 116) shows, indeed, that the saddlebacks have not only been considerably reduced, but are even beginning to develop into valleys; while the synclines, on the other hand, have experienced less erosion, those with approximately vertical axes appearing as dominant heights.

Excellent examples of the same phenomena are furnished by the Carpathians—a mountain-chain also

FIG. 51. SECTION ACROSS WESTERN PART OF THE JURA MOUNTAINS (Heim, after P. Choffat).

Symmetrical and unsymmetrical flexures.

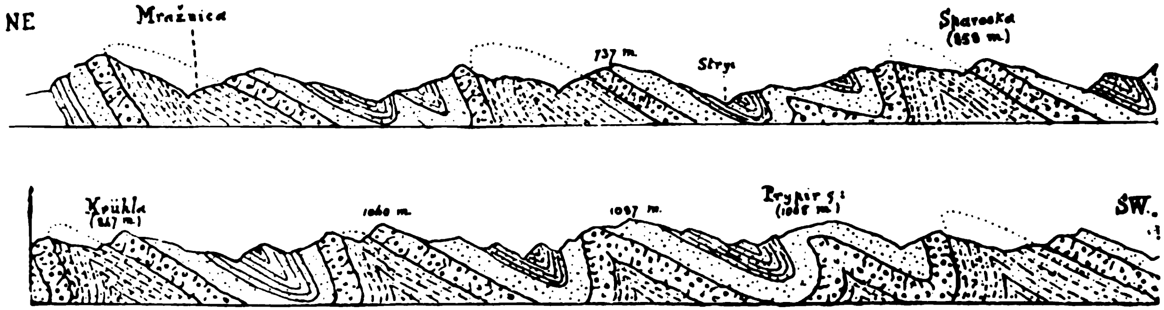

FIG. 52. SECTION ACROSS PART OF THE SANDSTONE ZONE OF THE MIDDLE CARPATHIANS (Vacek).

Isoclinal folds. The strata are of Cretaceous and Tertiary age.

of relatively recent age. Fig. 52 (p. 116) exhibits the structure of a part of the chain in which the folds are unsymmetrical. Here it will be observed that the tops of the anticlines have in every case been greatly reduced; but the synclines, owing to the isoclinal arrangements of the strata, do not tend to develop into hills. In point of fact, unsymmetrically folded strata behave very much in the same way as beds having a persistent dip in one direction. When the anticlines have been truncated the strata appear at the surface as a series of isoclinal beds, some of which are relatively more resistant than others. In time, therefore, these harder beds crop out as well-marked ridges or escarpments, according as the angle of dip is high or relatively low. But no sooner do the axes of the folds approach the vertical, and the flexures become symmetrical, than the superior strength of the synclinal structure at once asserts itself. This is well illustrated by Fig. 53, where we have a series of syn-

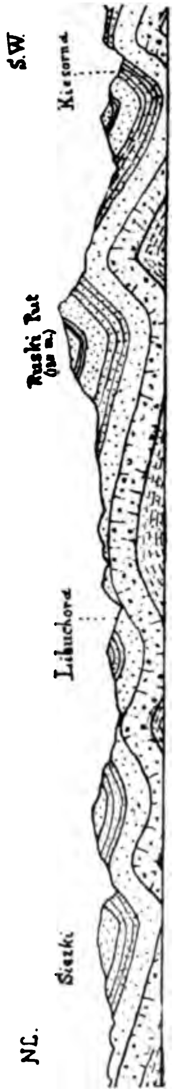

FIG. 53. SECTION ACROSS PART OF THE MIDDLE CARPATHIANS (Vacek).

Symmetrical synclines forming mountains. This section crosses another portion of the Sandstone Zone shown in Fig. 52.

Fig. 54. Section across the Appalachian Ridges of Pennsylvania. (H. D. Rogers.) Synclinal mountains and anticlinal hollows.

clinal troughs forming conspicuous mountains, while the intermediate anticlines correspond for the most part with valleys and depressions.

If it be true, therefore, that the denudation of young mountains, such as the Alps and the Carpathians, has been guided and determined to a large extent by geological structure, we ought to meet with still stronger evidence of a like kind in mountain-ranges of greater antiquity. The mountain-systems we have been considering are of Cænozoic age; they are among the latest great upheavals of the world. We see in the Appalachian Chain of North America a very much older system, for it came into existence about the close of Palæozoic times. Being of such enormous antiquity, the Appalachians ought to give evidence of correspondingly great denudation. All the weak geological structures should have collapsed and disappeared ages ago; the heights ought not to coincide with anticlines. The accompanying section across a portion of the chain in Pennsylvania shows that this has actually happened, symmetrical synclines having as usual developed into hills, while anticlines have been degraded.

Similar evidence might be adduced from

many other regions, but enough has been advanced to show that in the process of erosion and denudation of mountains of uplift, anticlines, as compared with synclines, are essentially weak structures. When the flexures are symmetrical the synclines tend to be carved into hills, but when the axes are inclined the strata often give rise to a series of prominent escarpments or to a succession of ridges with intervening hollows, the escarpments and ridges corresponding to the outcrops of the more resistant rocks. (Fig. 55.)

Comparing mountain-chain with mountain-chain, we find, as might have been expected, that the oldest mountains, if they are the least prominent, are at the same time the most stable. They have endured so long that much of their primeval elevation has been lost; the weakly built structures have been demolished, and only the stronger now remain. Great rock-falls and landslips are therefore seldom heard of among such mountains. It is quite otherwise with the younger uplifts of the globe. The valleys of the Alps, the Caucasus, the Himalayas, the Cordilleras, and other chains of relatively recent age are cumbered with chaotic heaps of fallen rock-masses. From time to time peaks and whole mountain-sides collapse and slide into the valleys; and this rapid degradation will continue until every weak structure has been removed. The hills and mountains of our own country have long since passed through this phase of unstable equilibrium. In the younger mountain-chains of the globe underground structure and superficial configuration

still to a certain extent coincide, but in the more ancient and therefore more highly denuded mountain-systems such coincidence is of very rare occurrence. Anticlinal mountains built up of porous and relatively impermeable strata are restricted to regions of recent uplift, and have no long life before them.

We have seen that in the case of plains and plateaux of accumulation the original surface of the ground is an expression of the geological structure, the general direction of their drainage-systems being determined

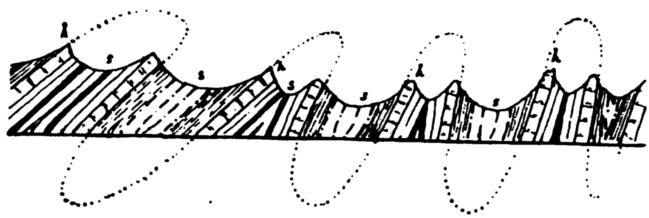

FIG. 55. UNSYMMETRICAL FOLDS, GIVING RISE TO ESCARPMENTS AND RIDGES.
h h, hard beds ; *s s*, soft beds.

by the average inclination of the strata. The same is no doubt to a large extent true of regions of mountainous uplift; the shape of the surface and the direction of the streams and rivers must at first have been determined by the arrangement or architecture of the rocks. But while it is comparatively easy to realise the conditions that obtained in a plateau-country during the early stages of its existence, it is very much harder to picture to ourselves the general aspect which a mountain-chain must have presented at the time of its upheaval. We are justified by the evidence

in believing that the larger inequalities of the surface must often have coincided with corresponding flexures and other deformations of the strata. But we need not suppose that all the convolutions, fractures, and displacements now laid bare in precipice and gorge actually appeared as such at the surface. Laboratory experiments have shown that a great deal of flexing, folding, contortion, and displacement may take place underground, while the surface simply swells up or bulges. And that may quite well have been the case with many mountain-chains. Yet we cannot ignore the possibility or probability that folding and displacement of strata may sometimes have resulted in wholesale rupture and confusion at the surface. We need not wonder, therefore, if we sometimes find it hard to account for certain vagaries in the drainage-systems of mountain-chains. Even the youngest of these chains has experienced so much denudation, that it is often impossible to realise the surface-conditions which may have determined the initial directions of the rivers. The longitudinal watercourses doubtless follow the axial arrangement of the strata, some of them occupying structural hollows (synclines), while others run along the backs of anticlines, or follow the outcrops of relatively softer rocks. The origin of certain transverse river-courses is harder to understand. Some of these may cut across a succession of great ridges; they break through the mountains in such a way as to suggest that they are perhaps following a line of fracture. Most commonly, however, this

is certainly not the case. Sometimes it can be shown, as already indicated, that a transverse stream has simply eaten its way back into the heart of the mountain-ridge, which it has eventually breached or "gapped," and so worn down as to encroach upon the drainage-area of some adjacent longitudinal valley. Transverse streams working back in this way have not infrequently captured longitudinal rivers, which thus appear to mysteriously forsake their own valley in order to break through a mountain-ridge. Perhaps most of the sudden changes in direction of Alpine rivers are illustrations of this system of capture. It is possible, however, as some geologists have supposed, that certain transverse river-courses may have been determined by the presence of a series of minor crustal folds, arranged at right angles to the main or longitudinal flexures of a mountain-chain. But we know so little of the actual conditions of surface that obtained when such a chain was being upheaved, that we must often be content to remain in ignorance of the causes that may have led to the sudden deflection of a river across a mountain-ridge. When we bear in mind, however, that the present lines of drainage can agree only in a general way with those that came into existence at the birth of a chain—that many anticlinal arches, now laid bare and deeply eroded, may never have shown at the original surface—it is not hard to understand how certain transverse river-courses may have come to intersect a succession of ridges. In many cases such courses may really indicate the

primeval inclination of the ground, the rivers having cut their way at first without any reference to deeply buried structures, which were only to be exposed later on during the general process of denudation.

Although we may vainly endeavour to trace the history of all the river-courses of a mountain-chain, we need be in no doubt as to the ultimate fate of the mountains themselves. It is more difficult certainly to discover the various stages in the erosion of a mountain-system than in that of a plateau of accumulation; but we are assured that all elevated lands, whatsoever their origin, tend to be lowered to their base-level. Should that base-level be steadfastly maintained, mountains and plateaux alike must eventually be reduced to the condition of plains of erosion. But the modifications of the surface of a mountain-region developed during the process of erosion are infinitely complex. This is due partly to the very varied composition of the rocks, and partly to the complicated geological structure.

The surface-features of a denuded plateau of accumulation have a general sameness; there is little variety in the form of the hills and mountains—all are more or less pyramidal. In regions of gently inclined and undulating strata the features due to erosion are more diversified, and this diversity becomes greater as the dips of the strata increase and change rapidly in direction. The foothills that flank the base of so many mountains of uplift are composed very often of symmetrically folded strata, but as

we pass inwards to the main chain the folds become steeper and unsymmetrical, and the structure is rendered still more complex by vast overthrusts and shearing-planes. As the structural complexity increases, and the rocks are thrown and twisted into every possible position, the surface-features are constantly changing, so as to show, often within narrow limits, every variety of cliff and ridge and peak. We see then that it is geological structure chiefly that determines the form of the ground; and since the inclination, the folding, and the shearing of rocks must be attributed to crustal movement, it is clear that hypogene action has played a most important part in the formation of mountains. We may say with truth that all true mountain-ranges owe their origin to deformation of the crust. But the shape which they ultimately assume is solely the result of erosion. It is hypogene action which provides the rough blocks; it is by epigene action that these are subsequently carved and chiselled, the forms of the sculptured masses being determined by the nature and structure of their materials. In regions of recent uplift, the process of sculpturing, although considerably advanced, has not yet sufficed to obliterate the original or primeval shape of all the masses. But in elevated tracts of great antiquity the land-blocks have been entirely remodelled. In the general lowering of the surface by denudation, mountain-masses have been removed, and what were formerly depressed areas now often appear as dominant elevations. Mountains

of recent uplift are characterised by steep profiles, by peaks and knife-edged arêtes; the structures are often unstable, and yield readily to the agents of erosion, so that rock-falls and landslips are constantly taking place. In regions of ancient uplift, on the other hand, the profiles are generally softer; peaks and sharp-crested ridges are of less frequent occurrence, weak structures have disappeared, and the degradation of the mountains does not advance so rapidly. The levelling process, however, though slower, is quite apparent. The valleys are widened and deepened, the mountains crumble down, and, should the base-level of erosion be retained, the whole area will eventually be flattened out and resolved into a plain of erosion.

Such then are the several stages through which a region of mountain-uplift must pass. First comes the stage of youth, when the surface configuration corresponds more or less closely with the underground structure. Next succeeds the stage of middle-life, when such coincidence is all but obliterated, when the valleys of youth have been exalted and its mountains have been laid low. Last comes old age and final dissolution, when the whole region has been reduced to its base-level. But the decay of a mountain-chain does not always proceed without interruption. Not infrequently the base-level is disturbed; new horizontal movements of the crust take place, and bulging-up of the region is accompanied by further folding and fracturing of the strata. The mountain-system

renews its youth. On the other hand, the old base-level may be destroyed by subsidence of the crust, and the mountains, partially or wholly drowned, may in time become largely buried under new accumulations of sediment. Re-elevation taking place, erosion recommences, and the degradation of the region is resumed. In the structure of not a few mountain-

FIG. 56. STRUCTURE OF THE ARDENNES (after Cornet and Briart).

MM, the existing surface; the light-shaded area above this level represents the rock-masses removed by denudation. The Silurian rocks at the base of the section are indicated by thin white lines. Above these, on the left-hand side of the section, between *C* and *M*, come Devonian conglomerate, sandstone, shale, and limestone; next in succession follow the Carboniferous strata at and above *M*; *A A*, *B B*, *C C*, are dislocations.

chains we may read the history of many such vicissitudes.

So completely have some mountains been removed

by denudation, that without some knowledge of geological structure we should never have divined their former existence. An instructive example is furnished by the Carboniferous tracts of Belgium and Northern France. The structure of these regions shows that formerly a considerable range of mountains extended between Boulogne and Aix-la-Chapelle. At or towards the close of Carboniferous times a great earth-movement, acting in a direction from south to north, buckled up the strata, and these, yielding to the pressure, snapped across, and extensive overthrusting followed along the line referred to, the Carboniferous beds being inverted and overlaid by Devonian strata. The mountains of upheaval which thus came into existence attained a great elevation, the higher parts of the range reaching probably not less than 16,000 or 18,000 feet. The section (Fig. 56) will show how completely the surface has been remodelled, how mountains of elevation have been replaced by a plain of erosion.

CHAPTER VI

LAND-FORMS IN REGIONS OF HIGHLY FOLDED AND DISTURBED STRATA (*continued*)

STRUCTURE AND CONFIGURATION OF PLATEAUX OF EROSION—FORMS ASSUMED UNDER DENUDATION—MOUNTAINS OF CIRCUMDENUDATION—HISTORY OF CERTAIN PLATEAUX OF EROSION—SOUTHERN UPLANDS AND NORTHERN HIGHLANDS OF SCOTLAND—STAGES IN EROSION OF TABLE-LANDS.

IN our last chapter we considered the history of a mountain-chain, following that history from the stage of youth to old age and final dissolution. This last we recognised in the plain of erosion. We have next to trace the subsequent history of such a plain. The geological structure of many mountain-chains, as already indicated, reveals the fact that these are often the result of more than one uplift. After having been for long ages subjected to erosion, and even to subsequent subsidence and sedimentation, the same region has again yielded to lateral crush, and new series of folds and thrust-planes have come into existence. But the crust does not always yield in this particular fashion. Not infrequently relief from pressure is obtained by widespread bulging-up of the surface, one or more broad swellings with perhaps corresponding

broad depressions appear, instead of an intricate arrangement of more or less closely compressed folds. We may for convenience' sake speak of the latter as resulting from *axial* uplift, and of the former as due to *regional* uplift, even although it be obvious that in most wide regions of uplift there must be an axis or line of maximum movement.

Now it can be shown that one and the same region has not infrequently experienced both kinds of uplift. Axial uplifts have in time been succeeded by regional uplifts; for again and again we encounter ancient

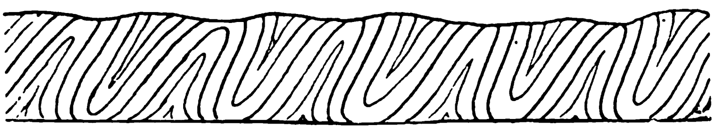

FIG 57. DIAGRAMMATIC SECTION ACROSS A PLATEAU OF EROSION.
Isoclinal folds.

plains of erosion occurring at various levels above the sea, their geological structure showing clearly that they have replaced old mountains of complicated structure. Such elevated plains may be termed plateaux or table-lands of erosion, to distinguish them from plateaux of accumulation or deposit. The characteristic feature of the latter, it will be remembered, is the general coincidence of the surface with the underground structure, while the former shows no such correspondence. The structure of a tableland of erosion may thus be represented as in Fig 57.

Many such table-lands are recognised in Europe, the Highlands and Southern Uplands of Scotland

and the Scandinavian plateaux being good examples. Ancient plateaux of the kind are all more or less denuded, trenched, and furrowed by valleys to such an extent that the plateau character is often somewhat obscured. For no sooner is a plain of erosion uplifted than a new cycle of erosion begins. The direction of the drainage is determined, in the first place, by the slope of the ground, and this we can readily understand may be somewhat diversified. The surface may be canted either in one direction only, or in more than one, for the crustal movement is unlikely to be equal in amount throughout the whole region of uplift. Hence, the primeval rivers may all flow in one particular direction, or they may trend to various points of the compass. However that may be, it is certain that in course of time they must gradually deepen their valleys, and the plateau must eventually come to be cut up very much in the same way as a plateau of accumulation. But the mountains of circumdenudation resulting from this process will differ considerably in character from those carved out of horizontal strata. The varying structure of the rocks will necessarily influence erosion, and thus lead to a greater diversity of form. Should the strata be steeply inclined, and this will usually be the case, then it is obvious that the harder masses must come in time to project beyond the more readily reduced rocks with which they are associated. The general surface of the plateau will thus tend to assume a corduroy configuration, the long ridges coinciding with

the outcrops of the "harder rocks," while the intervening parallel hollows will correspond with the outcrops of the more yielding strata. In short, the land-features evolved by denudation will have a general resemblance to those produced in a region of slightly inclined and gently undulating formations. But owing to the very varied character of the rocks and their more complicated structures, the surface-features of a plateau of erosion will be more pronounced and much more irregular. In such a region the larger rivers, being frequently of primeval origin, will often be found to cut across mountain-ridge after mountain-ridge, and to follow courses more or less transverse to the corduroy surface. Others may keep closely to the outcrops, and run in the direction of the "strike" or trend of the strata, while some may take now one route and now another. The original surface of the plateau will generally be indicated by the direction of the main drainage-lines or principal rivers, while the subsequent slopes due to erosion will usually be manifested by the course of tributary streams. During the progress of denudation, however, many modifications of the drainage will be brought about. Cases of the capture of principal rivers by lateral streams working their way back or across the strike can hardly fail to occur, and these and other changes may render the original drainage-lines obscure and hard to trace.

To such an extent have many ancient plateaux of erosion been denuded, so deeply have they been

trenched, that their surface has become resolved into a truly mountainous region, wherein all the elevations are mountains of circumdenudation, the tops of which are the only remaining relics of the original plateau-surface. Such mountains, owing generally to the durability of their rocks and the strength of their structure, are not so readily demolished as the mountains in a range of recent uplift. They may not often emulate these in height and grandeur, their profiles may as a rule be less wild and irregular; but such is not always the case. When a plateau of erosion stands at a great elevation, the mountains carved out of it are apt to rival the boldest and most abrupt of Alpine heights. Such abrupt slopes and the profound valleys that intervene are the result of relatively rapid and powerful vertical erosion. But when a plateau has only a moderate elevation, the configuration of its mountains tends to be less abrupt, and to approximate in character to that attained by a true mountain-chain during the period of its maturity, when all weak structures have been demolished and the surface no longer coincides with the folds of the strata. And this is just what might have been expected, when it is borne in mind that in each case the fundamental geological structure is the same. A mountain-chain is composed mainly of highly flexed and folded rocks. Subjected to erosion, the whole region is remodelled and eventually reduced to a base-level. But the rock-structure remains; the plain of erosion is composed, just as the mountains were, of highly flexed and folded

rocks. When that plain is uplifted *en masse* to form a plateau it is obvious that epigene action must tend to evolve out of the plateau mountains and ridges which, in their form and alignment, will closely resemble those that existed over the same area before the old plain of erosion had come into existence. The rocks and rock-arrangements, being the same in both cases, must under denudation tend to produce a similar configuration. No doubt there might be certain contrasts, but these would not be due so much to geological structure as to changes in the character of the rocks. The planing away of great mountain-masses might well expose quite a different series of rocks, and these, when the region was again uplifted and carved into hill and valley, would doubtless weather differently from the rock-masses under which they formerly lay buried. But the general geological structure remaining the same, mountains and ridges would necessarily be developed along the old lines.

We may now consider the structure of certain plateaux of erosion which there is every reason for believing existed at one time as plains—plains which had previously replaced mountain-systems. A good example is ready to our hand in the Southern Uplands of Scotland—that belt of high ground which is drained by the Clyde, the Doon, and other streams flowing north-west, and by the Cree, the Dee, the Nith, and the Annan flowing south-east. The north-east section of the region is traversed by the Tweed, with an easterly to north-easterly course; while the extreme

south-west portion is watered by the Stinchar, flowing in a south-west direction. The whole area drained by those rivers and streams might be described as a broad undulating plateau, furrowed and trenched by narrower and wider valleys. The mountains are somewhat tame and monotonous—flat-topped elevations with broad, rounded shoulders and smooth grassy slopes. The rocks composing the region consist for the most part of greywackés and shales, the former being usually hard greyish-blue rocks arranged in beds of variable thickness. They are much more abundantly developed than the shales which are associated with them, although now and again the latter attain considerable importance. The strata usually dip at high angles, often approaching the vertical, and, the same beds coming again and again to the surface, it is obvious that we are dealing here with a vast succession of steeply inclined and closely pressed anticlinal and synclinal folds. In many natural exposures, as on the coast and in the valleys, the intensely folded character of the strata is clearly revealed. Obviously the strata have been squeezed together, and affected in precisely the same way as the rocks of the Alps. Frequently, indeed, we find that overthrusting has taken place, the rocks having yielded to tangential pressure by shearing. The general trend or "strike" of the strata is from south-west to north-east, while the dip is sometimes north-west, sometimes south-east, changing now and again very rapidly, at other times remaining constant for long distances. In the former

case the folds are not infrequently approximately symmetrical; in the latter they are necessarily unsymmetrical. In a word, the geological structure is that which characterises all mountains of elevation like the Alps. Nor can we reasonably doubt that when the folding and fracturing took place the crust bulged up and a series of superficial ridges and hollows—a true mountain-chain—came into existence. That was a very long time ago, however, for the uplift dates back towards the close of Silurian times. Then followed a protracted period of denudation, during which our mountains of folded rocks must have passed through the various stages of adolescence, maturity, and old age. Much of the region was reduced to the condition of a low plain, diversified in part by swelling hills of less and greater height. All this work had been accomplished, and the degraded hills were continuing to crumble away, when the whole region was once more uplifted, and so converted into a table-land or plateau with an undulating surface. This movement of elevation had been completed, and renewed erosion had furrowed and trenched the plateau to some extent, before the beginning of Old Red Sandstone times, for the lowest or bottom beds of the Old Red Sandstone series here and there occupy valleys carved out of the underlying Silurian greywacké and shale. To what extent the plateau was submerged during the Old Red Sandstone period we cannot tell. Probably the submergence was greatest over the north-east portion of the region, for it is

FIG. 58. SECTION ACROSS PORTION OF SOUTHERN UPLANDS, SHOWING OLD RED SANDSTONE RESTING UPON PLAIN OF EROSION.

S, Silurian rocks; *D*, Old Red Sandstone; *C*, Carboniferous; *b*, basalt; *a*, agglomerate, etc.

in that quarter that we meet with the most extensive and continuous accumulations of Old Red Sandstone rocks. Be that as it may, we know that some time before the succeeding Carboniferous period re-elevation ensued and a new cycle of erosion was inaugurated, during which the Old Red Sandstone rocks and the underlying Silurian strata were more or less profoundly denuded. Thereafter followed an epoch of renewed subsidence on a more extensive scale, when much of the plateau was drowned in the Carboniferous sea, and marine sediments of that age were distributed over areas which had probably never been overflowed by the waters of Old Red Sandstone times. Judging from the present distribution of the Carboniferous strata, it seems likely that the plateau was, as before, more deeply submerged towards north-east and south-east than in other directions. So far as we can tell, the region has never since been

depressed below the sea, but in succeeding Permian and Triassic times long stretches of inland lakes or seas penetrated into the heart of the plateau, occupying hollows which were certainly in existence during the preceding Carboniferous period.

Such, without going into details, is a general outline of the chief changes which have taken place in the Southern Uplands of Scotland. A plateau which came into existence towards the end of the Silurian period might well be expected to show a highly denuded aspect. It is true that during Old Red Sandstone and Carboniferous times it was considerably depressed, and so escaped much erosion, but in the intervals separating those stages denudation must have been in active progress, as it has continued to be since the final disappearance of marine conditions. No doubt much rock has been removed from the whole surface of the region in question. Not only have wide and deep valleys been excavated, but the broad-backed hills and mountains can hardly fail to have been greatly reduced in height. It is still possible, however, to trace the general configuration of the original surface. The average slope of the plateau appears to have been towards the south-east. This is indicated by the direction of the principal rivers—the Annan, the Nith, the Ken, and the Cree. It is further shown by the distribution of the Old Red Sandstone and later geological formations. Thus strata of Old Red Standstone and Carboniferous age occupy the Merse and the lower reaches of Teviotdale,

and extend up the valleys of the Whiteadder and the Leader into the heart of the Silurian uplands. In like manner Permian sandstones are well developed in the ancient hollows of Annandale and Nithsdale. Along the northern borders of the Southern Uplands we meet with similar evidence to show that even as early as the Old Red Sandstone period the ancient plateau along what is now its northern margin was penetrated by valleys that drained towards the north. But the main water-parting then, as now, lay not far south of this northern margin[1]; in other words, the surface of the ancient plateau, a few miles back from its northern boundary, sloped persistently towards the south-east. Now the strike or general trend of the strata throughout the whole of these Uplands is south-west and north-east. We cannot doubt, therefore, that when the ancient plain of erosion was uplifted, and so became a plateau, the surface would be marked by many more or less well-defined ridges and hollows, probably none very prominent, but all having a north-east and south-west trend. The average slope of the surface being towards south-east, the

[1] Many modifications of the drainage have been effected which cannot be referred to here. It may be pointed out, however, that the head-waters of the Nith flow towards the north until they reach the broad Nithsdale, whence the drainage is directed south-east, so that Nithsdale may be said to cut right across the Uplands from north-west to south-east. This is probably a case of capture, the Nith, working back, having gradually invaded the northern drainage-area and captured such streams as the Afton and the Connel. The Clyde and the Doon are the only rivers of any size which have preserved their north-westerly course, and the head-waters of the former have just escaped capture by the Tweed.

flow of the principal rivers would follow that direction, they would cut their channels across the outcrops of the strata. But the "corduroy" character of the plateau would now and again lead to occasional deflections, while some streams and rivers would be conducted for long distances parallel to the strike of the strata. In a word, two sets of principal valleys would tend to be formed, namely, *transverse* and *longitudinal* valleys. Examples of the former have already been cited, such as the Cree, the Ken, and the Nith, and amongst the better-known longitudinal valleys may be mentioned those of the Teviot, the Ettrick, and the Yarrow. But a glance at any good map of the region will show that all the more important streams have a tendency to flow either in a transverse or a longitudinal direction, while many run now in one of these directions and now in the other.

The Southern Uplands thus prove to be merely a highly eroded plateau. Their geological structure shows that towards the close of Silurian times the greywackés and shales were buckled up, folded, and faulted, and doubtless appeared at first as a range of true mountains of elevation. Thereafter followed a prolonged period of erosion, interrupted, it is true, at successive stages by partial submergence, but resulting finally in the demolition of the old mountains of elevation and the conversion of the tract into a plain of erosion. Then came a final regional uplift, when that plain was converted into a plateau, which still exists, but in a highly denuded and eroded condition.

The Northern Highlands of Scotland might be cited as another plateau of erosion with a somewhat similar geological history. There, as in the south, there is evidence to show that vast earth-movements resulted, towards the close of Silurian times, in the formation of great mountains of elevation. The thrust-planes visible in the north-west part of that region are on a much more extensive scale than those met with in the Southern Uplands. Probably the mountains of elevation which appeared over the site of the present Highlands were loftier and bolder than the pre-Devonian heights of Southern Scotland. They may quite possibly have rivalled the Alps in grandeur, for the folding and general disturbance of the rocks are quite as remarkable as the confusion seen in the mountains of Switzerland. We may well believe that when the Highland mountains first uprose, their external form and internal structure would more or less closely coincide. No sooner had they come into existence, however, than the usual cycle of erosion would commence, and it is certain that after a prolonged interval they were to a large extent reduced to their base-level—much of the formerly elevated area acquiring the character of a plain of erosion. Subsidence next ensued, and that plain became gradually overspread with sediment, several thousand feet of Old Red Sandstone strata being deposited on the planed and abraded surface of the ancient rocks. At a subsequent date the whole region was uplifted and converted into dry land, forming a plateau country,

which, so far as we know, has never since been completely submerged, although it may well have experienced many oscillations of level.

It is out of that ancient plateau that the Highland mountains have been carved. The original surface-slope is, as usual in such cases, indicated partly by the direction of the principal drainage-lines and partly by the summits of the mountains, which decline in elevation as they are followed outwards in the direction of the chief lines of drainage. Again, the main water-partings separating the more extensive drainage-areas of the country mark out in like manner the dominant portions of the same old plateau-land. The water-parting of the North-west Highlands runs nearly north and south, keeping quite close to the western shore, so that nearly all the drainage of that region flows inland. The average inclination of that section of the Highlands is therefore easterly, towards Glenmore and the Moray Firth. In the region east of Glenmore the land slopes in the directions followed by the rivers Spey, Dee, and Tay. These two regions —the North-west and the South-east Highlands—are separated by the remarkable depression of Glenmore, running through Lochs Linnhe, Lochy, and Ness, and the further extension of which towards north-east is indicated by the straight coast-line of the Moray Firth as far as Tarbat Ness. This long depression marks a line of fracture and displacement of very great geological antiquity. The old plateau of the Highland area was fissured and split in two, that

portion which lay to the north-west sinking along the line of fissure to a great but unascertained depth.[1] Thus the waters that flowed down the slopes of the north-west portion of the fractured plateau were dammed by the long wall of rock that rose upon the south-east side of the fissure, and compelled to flow off to north-east and south-west along the line of displacement. The erosion thus induced sufficed in course of time to hollow out Glenmore and all the mountain-valleys that open upon it from the west.

The dominant portion of the ancient plateau east of the great fault is approximately indicated by a line drawn from Ben Nevis through the Cairngorm and Ben Muich Dhui Mountains to Kinnaird Point. North of that line the drainage is towards the Moray Firth; east of it the rivers discharge to the North Sea; while an irregular winding line, drawn from Ben Nevis eastward through the Moor of Rannoch, and southward to Ben Lomond, forms the water-parting between the North Sea and the Atlantic, and probably marks approximately another dominant area of the fractured table-land.

The geological structure of the Highlands agrees so far with that of the Southern Uplands, that the dominant "strike" of the strata is south-west and north-east. This, therefore, is the trend of the flexures and folds and of all the larger normal faults and great

[1] It is probable that movements have taken place again and again at different periods along this line of weakness, and these movements may not always have been in one direction.

thrust-planes. Now such a structure would naturally determine the disposition of the surface-features worked out by erosion. Before the beginning of the Old Red Sandstone period, the pre-existing mountains of uplift had been largely degraded to a base-level. Much of the region, in other words, had been converted into a plain of erosion, which subsequently became depressed and buried under thick accumulations of sediment, derived in chief part from the denudation of such parts of the Highland area as still remained in the condition of dry land. After the deposition of the Old Red Sandstone the whole region was elevated *en masse*, and converted into a plateau or table-land. The surface of that plateau would doubtless be somewhat undulating and diversified. Probably the "stumps" of the highly denuded mountains, which had supplied materials for the formation of the Old Red Sandstone, still formed dominant areas. But wide regions had been planed down, and these would be marked by a kind of "corduroy" structure—parallel lines of escarpment and ridges with intervening hollows, corresponding to the successive outcrops of "harder" and "softer" rocks. The regions overspread by the Old Red Sandstone, on the other hand, would be approximately level, sloping gently, however, towards the north, north-east, and south-east. We may, therefore, conceive the surface of the ancient Highland Plateau to have been from the first more irregular than that of the Southern Table-land. The primeval rivers would

doubtless follow the average slopes of the plateau, and would thus sometimes cross the outcrops at all angles, and sometimes flow in the direction of the strike for longer or shorter distances. The great depression on the line of the Caledonian Canal, although partially filled with the sediments of Old Red Sandstone times, probably still formed a well-marked feature at the surface of the plateau when this was first uplifted. And the same may well have been the case with many other lines of fracture. In short, although the average slope of the ground determined the general direction of the drainage, the corrugated and often much diversified surface of the plateau must have led to endless deflection of the water-flow. Again, as erosion proceeded, and the valleys were cut deeper and deeper, many modifications of the drainage would naturally arise, cases of the "capture" of one stream by another having been of common occurrence.

It is not, however, with the history of such changes that we have to do, but rather with the character of the existing valleys and mountains which have been carved and chiselled out of the ancient plateau. Of the valleys it may be said in general terms that they are all valleys of erosion. Many have been hollowed out along the outcrops, and are thus *longitudinal*, while others have been cut out across the "strike," and to this extent are *transverse*. Some of the former are of primeval antiquity: they correspond in direction not only with the strike of the strata, but with what seems to have been the original slope of the plateau,

the valley of the Spey being the most conspicuous example. The transverse valleys, represented typically by Glen Garry and the valley of the Tay, are obviously also of great age, since they in like manner indicate the general slope of the plateau in the regions where they occur. A large proportion of the longitudinal valleys that drain into these transverse valleys are in all probability of subsequent origin, although some of them may have been outlined at as early a date as the latter. Although none of the longitudinal valleys can be described as synclinal, they may all nevertheless be termed structural, inasmuch as they coincide with the strike of the rocks. So likewise we may term Glenmore a structural hollow, since it occurs along a line of fracture ; and the same is the case with Glen Docherty and Loch Maree. These lines of fractures no doubt showed at the surface of the plateau when it was first uplifted, and so determined the direction of drainage and erosion. But all the valleys as we now see them are valleys of erosion, their direction having been determined sometimes by the average slope of the plateau, sometimes by the geological structure.

The mountains of the Highlands are likewise monuments of erosion, owing their existence as such sometimes to the relative durability of their materials, sometimes to their geological structure, or to both causes combined. They are all, without exception, ***subsequent*** or *relict mountains.* Thus, in the following section from Glen Lyon to Carn Chois we see

that the present configuration of the surface does not coincide with the complicated underground structure. It is the same, indeed, throughout all the Highland area. Take a section across any portion of that region, and you shall find that the more continuous "ranges" are developed along the outcrops—they are, in short, escarpment mountains. So great has been the erosion, however, within such "ranges," that their alignment usually becomes obscured, and we are confronted by confused groups of mountains, drained by streams flowing in every possible direction. "Any

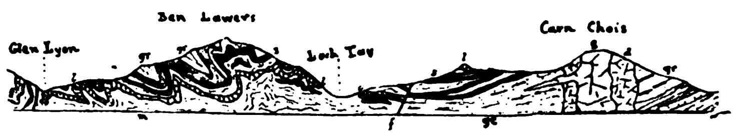

FIG. 59. SECTION FROM GLEN LYON TO CARN CHOIS. (*Geol. Survey.*)
m, mica-schist, etc.; *l*, limestone; *gr*, greywacké, etc.; *s*, amphibolite schist; *g*, granite; *d*, diorite; *f*, fault.

wide tract of the Highlands," as we have elsewhere remarked, "when viewed from a commanding position, looks like a tumbled ocean, in which the waves appear to be moving in all directions. One is also impressed with the fact that the undulations of the surface, however interrupted they may be, are broad; the mountains, however much they may vary in their configuration according to the character of the rocks, are massive and generally round-shouldered, and often somewhat flat-topped; while there is no great disparity of height amongst the dominant points of any individual group. Let us take, for example, the knot

of mountains between Loch Maree and Loch Torridon. There we have a cluster of eight mountain-masses, the summits of which do not differ much in elevation. Thus in Llathach two points reach 3358 feet and 3486 feet; in Beinn Alligin there are also two points reaching 3021 feet and 3232 feet respectively; in Beinn Dearg we have a height of 2995 feet; in Beinn Eighe are three dominant points, 3188 feet, 3217 feet, and 3309 feet. The four masses to the north are somewhat lower, their elevations being 2860 feet, 2370 feet, and 2892 feet. The mountains of Lochaber and the Monadhliath Mountains exhibit similar relationships; and the same holds good with all the mountain-groups of the Highlands. One cannot doubt that such relationship is the result of denudation. The mountains are monuments of erosion; they are the wreck of an old table-land, the upper surface and original height of which are approximately indicated by the summits of the various mountain-masses and the direction of the principal rivers. If we in imagination fill up the valleys with the rock-material which formerly occupied their place, we shall in some measure restore the general aspect of the Highland area before its mountains began to be shaped out by Nature's saws and chisels."

A table-land of erosion, long exposed to denudation, must obviously pass through the same phases as a plateau of accumulation. The elevated plain of complicated geological structure is first traversed by

rivers, the courses of which are determined by the average slope of the land. As valleys are deepened and widened, and the whole surface comes under the influence of the epigene agents, new tributary streams continue from time to time to make their appearance, and eventually a perfect network of drainage-lines is established. Wherever the rocks yield most readily to erosion hollows are formed, and many of these will necessarily coincide with the outcrop or strike of the strata. Longitudinal valleys thus tend to be developed. As denudation proceeds, the capture of streams by rivers and of rivers by streams often takes place, and the hydrographic system becomes more or less modified, but the general direction of the chief lines of drainage remains unchanged. Eventually transverse rivers are found cutting across mountain-ridge after mountain-ridge, the latter having only been developed after the rivers had come into existence. With the deepening and widening of the main valleys, and the continual multiplication of subsidiary hollows by springs, torrents, and streams, the whole plateau eventually becomes cut up into irregular segments of every shape, form, and size—a rolling mountain-land. Waterfalls, rapids, and other irregularities have now disappeared from the courses of the older rivers and streams, except, it may be, towards their heads, where more or less numerous feeders are busy cutting their way back into the mountains. Should the base-level be maintained, the process of denudation must continue until

the rolling mountain-land is finally reduced and resolved once more into a plain of erosion.

It is seldom, however, that a cycle of erosion is allowed to pass through all its stages. The study of many ancient plateaux has shown that the base-level is not infrequently disturbed—sometimes by elevation, at other times by depression. Long before the eroded plateau has been completely reduced, subsidence may ensue, and the drowned land may then become buried under vast accumulations of marine sediments. Should the region be once more upheaved and converted into dry land, streams and rivers will again come into existence, and flow in directions determined by the slopes of the surface. Thus ere long another hydrographic system will be developed which may differ entirely from its predecessor, both as regards direction and arrangement. As the rivers cut their way down through the superimposed marine strata they will eventually reach the buried land-surface, across which they will run without any reference to the former configuration. Should the base-level remain unchanged, a time will come when the overlying marine strata will be entirely removed, but the direction and general arrangement of the river-system acquired when the land was newborn will be maintained. Thus the direction of many transverse rivers, which in ancient plateau-lands are found cutting across mountains of every shape and disposition, have not infrequently been determined by the surface-slope of overlying masses, almost every vestige of which has since disappeared.

CHAPTER VII

LAND-FORMS IN REGIONS AFFECTED BY NORMAL FAULTS OR VERTICAL DISPLACEMENTS

NORMAL FAULTS, GENERAL FEATURES OF—THEIR CONNECTION WITH FOLDS—THEIR ORIGIN—HOW THEY AFFECT THE SURFACE—FAULTS OF THE COLORADO REGION, AND OF THE GREAT BASIN—DEPRESSION OF THE DEAD SEA AND THE JORDAN—LAKE-DEPRESSIONS OF EAST AFRICA—FAULTS OF BRITISH COAL-FIELDS—BOUNDING FAULTS OF SCOTTISH HIGHLANDS AND LOWLANDS — FAULT-BOUNDED MOUNTAINS — GENERAL CONCLUSIONS.

IN Chapter III. a short account was given of the dislocations or fractures by which rocks are frequently traversed. These, as we saw, are of two kinds—*normal faults* and *reversed faults* or *overthrusts.* The latter have been sufficiently referred to in connection with the appearances presented by highly flexured strata, amongst which, indeed, they are most usually encountered. Normal faults of various importance may likewise often be seen traversing areas of disturbed and contorted rocks. When such is the case, however, the larger of these faults not infrequently prove to be of later date than the flexures and thrust-planes. The latter are the result

of former horizontal movements of the crust; the normal faults, on the other hand, are vertical displacements due to later movements of direct subsidence. It will be understood, therefore, that reversed faults or overthrusts are practically confined to regions of highly flexed and contorted strata, while normal faults traverse every kind of geological structure. The latter, however, are certainly best displayed in areas of horizontal and moderately inclined strata, while they often form lines of separation between these and contiguous areas of highly disturbed rock-masses.

The amount of downthrow of normal faults is very variable. Sometimes it does not exceed a few feet or yards, in other cases it may reach thousands of feet, so that strata of vastly different ages may be brought into juxtaposition. The smaller faults usually extend for very short distances, while the larger ones may continue for hundreds or even thousands of miles. The course of great faults is usually approximately straight, but not infrequently it is curved. Very often they are accompanied by a series of smaller parallel dislocations; and now and again, in place of one great fault, with accompanying minor dislocations, we may find a series of more or less closely set parallel minor faults. When the downthrow of all these minor faults is in one and the same direction, the result is practically the same as if there had been only one major dislocation with a large downthrow. Another fact may be noted: faults, especially large ones, often split up, as it were, into

two or more. A major fault may begin as a mere crack or fracture, with little or no accompanying rock-displacement. But as it continues the amount of downthrow gradually increases until a maximum is reached, after which the displacement usually decreases until finally the fault dies out. In not a few cases, however, the degree of downthrow varies very irregularly.

Frequently faults are intimately connected with folds and flexures. This is shown at once by the fact that large dislocations very often trend in the same direction as the *strike* of the strata. Now and again, indeed, when a large fault can be followed to the end, it is found gradually to die out in a fold or flexure. In other words, what is a fault in one place is represented elsewhere by a flexure. It is not hard to see how that should be. Strain or tension must obviously be set up along the margin of a sinking area. If, for example, subsidence should take place within an area of horizontal strata, the horizontal position of the rocks along the margin of the sinking area will be interfered with. The pull or drag of the descending mass will cause the strata of the adjacent relatively stable area either to bend over or snap across. Should the movement be slow and protracted, the rocks will probably at first yield by bending; but as the movement continues they will eventually give way, and a fold will thus be replaced by a fracture. Towards either end of such a fault, therefore, we should expect it to die out into a simple

flexure or monoclinal fold. Probably most normal faults are in this way preceded by folding, except in cases where they have been more or less suddenly produced.

Although normal faults may be looked upon as the result of direct subsidence, it is obvious that in some cases they may well have resulted from movements of elevation. During the slow uplifting of a broad plateau strain and tension will come into play along the margin of the rising area. Folds will thus be formed, and these will be replaced eventually by fractures and displacements. The resulting structure

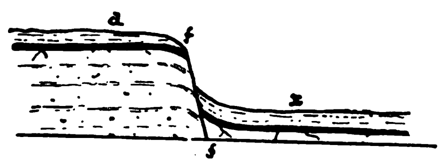

FIG. 60. SECTION OF NORMAL FAULT.

will thus be practically the same as if the folding and faulting had been produced by a movement of subsidence. Thus in Fig. 60 the fault *f* might have been caused either by the direct subsidence of the strata at *x* or by the elevation of the strata at *a*.

There is reason to believe that some large faults have resulted from crustal movements continued through long periods of time. The rock-displacements may have been very slowly and gradually effected, or the movement may have been more rapid, but interrupted again and again by longer or shorter pauses. Or, again, the rate of movement may have

varied from time to time, and occasionally it may even have been sudden and catastrophic. But such evidence as we have would lead us to infer that vertical displacements, whether the result of downward or of upward movements, have not been more rapidly effected than horizontal deformations. No doubt a sudden dislocation of the crust of large extent would show directly at the surface. But somewhat similar results would follow if the dislocation, without being quite sudden, were yet to be developed more rapidly than the rate of superficial erosion and denudation. Cases of the kind are well known, and to some of these reference will presently be made. It is with faulted rocks, however, as with folded mountains: when movement has ceased the inequalities caused at the earth's surface tend to be reduced and greatly modified. The epigene forces are untiring in their action, so that in course of time areas of direct subsidence tend to become filled up and the surrounding high-lying tracts to be worn down. To such an extent has this taken place, that in the case of certain great faults of high geological antiquity no inequality at the surface indicates their presence, and it is only by studying the geological structure that we are able to ascertain that such dislocations exist.

Bearing in mind the activity of the denuding agents, we might expect that normal faults of geologically recent date should show most prominently at the surface. And this to a large extent is doubtless true. Nevertheless, as we shall learn by-and-by, there are certain

faults of prodigious antiquity which still cause very marked inequalities at the surface. These often form the boundaries between highlands and lowlands. In such cases, however, the disparity of level is due not so much to vertical displacement, as to the fact that the lowlands are usually composed of less enduring materials than those which enter into the framework of the adjacent highlands. When a fault of great age traverses strata of much the same consistency (say sandstones and shales), the rocks on either side of the dislocation, we find, have been planed down to

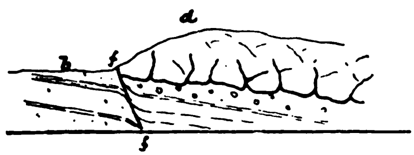

FIG. 61. NORMAL FAULT, WITH HIGH GROUND ON DOWNTHROW SIDE.

the same level. Thus in the low-lying coal-fields of Scotland the gently undulating surface gives no indication of the presence of the numerous dislocations which have been detected underground. Downthrows of hundreds of feet give rise to no superficial inequalities. It is only when one of these faults has brought relatively hard and soft rocks into juxtaposition that a marked surface-feature results. And in this case the hard rock invariably rises above the level of the soft rock, no matter on which side of the dislocation it happens to lie. Thus in Fig. 61 the hard rock *a* forms an eminence, although it is on the downthrow side of the fault, simply because it has withstood denud-

ation more effectually than the soft rock (*b*). In Fig. 62, again, it is obvious that the high ground at *x* owes its origin to the presence of the relatively hard rock (*h*). To this matter, however, we shall return in the sequel. Meanwhile we must consider, first, the appearances presented in regions where vertical movements of the crust have taken place within relatively recent times.

The Colorado Plateau affords some excellent examples of simple folds and normal faults of comparatively recent age. These have often profoundly affected the surface, lines of cliffs and bold escarpments rising along the high side of each dislocation.

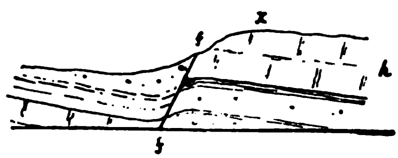

FIG. 62. NORMAL FAULT, WITH HIGH GROUND ON UPCAST SIDE.

The plateau, in short, has been split across by well-marked normal faults, some of which can be followed for hundreds of miles. Yet the strata on both sides of such dislocations are of much the same character and consistency. Here, then, it might be supposed that the fracturing and displacement had been suddenly effected. There is striking evidence, however, to show that such has not been the case. Although some of the faults referred to have a downthrow of several thousand feet, yet they have had no effect in disturbing the course of the Colorado River, which traverses the faulted region. The same, as we have seen,

holds true with regard to the flexures of that area. It is obvious, in a word, that the process of flexuring and faulting has proceeded so slowly that the river has been able to saw its way across the inequalities as fast as these appeared. But while the rate of river erosion has equalled that of crustal movement, the denudation of the plateau outside of the river-courses has not. Deformation and dislocation of the plateau have thus given rise to marked surface-features. Yet even in the case of these relatively young faults we find that the features determined by them have been very considerably modified by denudation. In the following section, for example, we see three

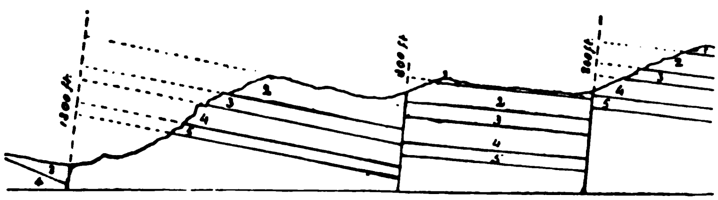

FIG. 63. FAULTS IN QUEANTOWEEP VALLEY, GRAND CAÑON DISTRICT. (Dutton.)

faults of 1300 feet, 300 feet, and 800 feet displacement respectively traversing the same series of strata, and yet giving rise to marked inequalities at the surface. The dotted lines, however, show to what an extent these features have been modified by denudation. There is an obvious tendency of the escarpments and cliffs to become benched back as they retreat, so that they do not show the abrupt character which they would have possessed had no superficial waste accom-

panied and succeeded the crustal movements. (See Fig. 63.)

In the Great Basin that extends between the bold escarpment of the Sierra Nevada, on the one hand, and the Wahsatch Mountains on the other, we encounter another series of large faults, which have determined the leading features of the region. It would appear that the area of the Great Basin formerly attained a considerably greater elevation than at present. Towards the close of Tertiary times the whole of this area, including the adjacent Sierra Nevada and the Wahsatch Mountains, was upheaved in the form of a broad arch. The crust thus subject to tension yielded by cracking across, and a system of long parallel north and south fissures was formed. In other words, the broad arch was split into a series of oblong blocks many miles in extent. When the movement of elevation ceased and subsidence ensued, the shattered crust settled down unequally between the Sierra Nevada in the west and the Wahsatch Mountains in the east. The amount of displacement along the margins of the Great Basin is very great; the fault at the base of the Sierra, for example, is estimated to be not less than 15,000 feet, while that which severs the Basin from the Wahsatch Mountains is also very great. The numerous parallel ranges that diversify the surface of the Great Basin itself are simply oblong crust-blocks, brought into position by normal faults. Being of so recent an age, they have suffered comparatively little modification.

Nevertheless, they do not fail to show the tool-marks of epigene action—everywhere escarpments are retreating, and one can see that already vast masses of rock have been removed from the surface. The accompanying diagram (Fig. 64) will serve to give a general idea of the geological structure of the Basin ranges. There is no reason to believe that the crustal movements above referred to were sudden or catastrophic in character. Probably they were no more rapid than those which have affected the plateau of the Colorado.

We are not without evidence of similar recent dislocations in the Old World, and there as elsewhere they give rise to more or less pronounced surface-features. One of the most interesting examples is seen in the great depression that extends northwards from the Gulf of Akabah by the Wâdy el Arabah, the Dead Sea, the valley of the Jordan, and Lake Tiberias. This long hollow would appear to

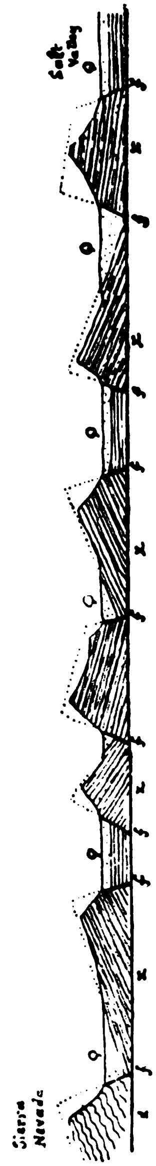

FIG. 64. RANGES OF THE GREAT BASIN. (Hinman, after Gilbert.) (Length of section, 120 miles.)

Q, Quaternary deposits; x x, granite, schists, and bedded rocks of various age; f f, faults. Each mountain is a "uniclinal orographic block," tilted in the direction indicated by the close lines; the latter, therefore, do not represent bedding. The diagram shows merely the general disposition of the disrupted rock-masses, and not the geological structure of each individual fault-block.

have come into existence at or about the close of Tertiary times. It is everywhere bounded by normal faults or by steep monoclinal folds, the one kind of structure passing into the other. Before this depression came into existence the region it now traverses appears to have been a broad continuous plateau, built up of ancient crystalline and Palæozoic rocks below, and approximately horizontal strata of Mesozoic age above. At what particular date this plateau of accumulation first appeared, and how long it remained undisturbed, we cannot tell. Possibly the movement of subsidence to which the Dead Sea owes its origin may have coincided with the upheaval that resulted in the formation of the plateau. However that may have been, the latter was eventually traversed by a series of monoclinal folds and parallel faults, and between these the great depression of the Jordan came into existence. The Mesozoic strata of the plateau retain their approximately horizontal position close up to the depression along its eastern margin, while the descent from the west is much less abrupt. But this is only broadly true. When the region is more closely investigated, the relatively gentle dip of the strata along the west side of the depression is found to be interrupted again and again by more or less sharp monoclinal folds and by normal faults, the presence of which is betrayed at the surface by corresponding sudden changes in the form of the ground. In other words, the descent from the plateau on the west is often by a series of broader

and narrower terraces and escarpments, running parallel with the trend of the great hollow. The western margin of the Dead Sea, for example, is determined by a vertical displacement, similar in character to, but not so extensive as, that which bounds it on the east. The section (Fig. 65) will serve to illustrate the geological structures referred to.

The flexures and faults of this interesting region do not date beyond the close of the Tertiary period, and consequently there has not been sufficient time to allow of a complete modification of the surface by epigene action. The most conspicuous features of the district are determined by folds and fractures—underground structure and surface-configuration to a large extent coincide. But everywhere also we observe the evidence of erosion and denudation. Great sheets of rock have been gradually removed from the surface, which is seamed and scarred by innumerable ravines and water-

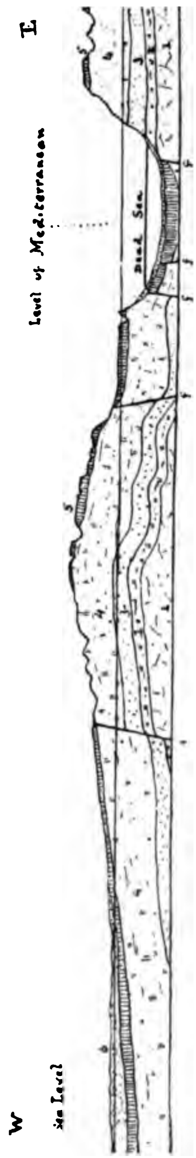

FIG. 65. SECTION FROM THE MEDITERRANEAN ACROSS THE MOUNTAINS OF PALESTINE TO THE MOUNTAINS OF MOAB. (After M. Blanckenhorn.) *1*, schistose and ancient igneous rocks; *2*, Carboniferous or Permian; *3, 4, 5*, Cretaceous strata; *6*, Tertiary; *f f*, faults.

courses, many of these being now dry and deserted. According to Professor Suess, the Jordan depression continues north between the Lebanon and the Anti-Lebanon, through the valley of the Nahr el Asi (the Orontes) to near Antioch. The same geologist is further of opinion that the great trough of the Red Sea and most of the lacustrine hollows of East Africa are in like manner due to direct subsidence of the crust, the probability being that they and the Jordan depression all belong to one and the same system of crustal deformation. It is noteworthy that the depressed areas of Africa lie in zones or belts having an approximately meridional direction, that they are not margined or surrounded by mountain-ranges, but are sunk in broad plateaux, and, moreover, are accompanied by abundant evidence of volcanic action. The troughs are mostly broad, and vary much and constantly in height above the sea, so that they are obviously not the result of erosion. In many places they are flanked on both sides by abrupt declivities comparable in character to those that overlook the Dead Sea. In some cases, however, steep bluffs and cliffs are confined to one side of a depression only. In short, we have in East Africa the same phenomena which confront us in Palestine. The earth's crust in all those regions has evidently yielded to strain or tension by snapping across and subsiding. In place of one simple normal fault, however, we see a complex system of parallel dislocations and flexures, the folded and shattered rocks having settled down un-

equally, while molten matter and loose ejecta issued here and there in less or greater abundance along the chief lines of rock-disturbance.

Similar geological structures on a smaller scale may be seen nearer home, and are well exemplified in the region of the Vosges and the Black Forest. These opposing mountains are the counterparts of each other, being built up of the same rocks, arranged in very much the same way. The basement rocks are granite and crystalline schistose rocks, which are overlaid by a series of Mesozoic strata. In the Vosges the dip of these strata is westerly, while the corresponding rocks in the Black Forest are inclined towards the east. Between the two ranges, as every-one knows, lies the basin of the upper Rhine, a basin which, like that of the Jordan, has been determined by a number of parallel normal faults. The Meso-zoic strata in the region surrounding the two ranges attain a thickness of at least 5000 feet, and there can be no doubt that these originally extended from west to east across what is now the basin of the Rhine. This is shown by the simple fact that the strata in question occupy that basin. (See Fig. 66, p. 164.) Doubtless the Mesozoic rocks were originally deposited in ap-proximately horizontal positions. Subsequently the sea retreated from the area, and a wide land-surface—probably an elevated plain or plateau—occupied its place. Eventually, in early Tertiary times, the region was subjected to crustal movements, and traversed from south to north by a series of dislocations, with

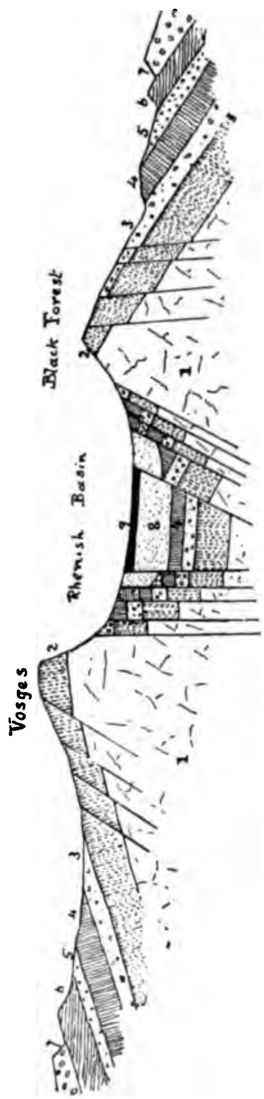

FIG. 66. SECTION ACROSS THE VOSGES AND THE BLACK FOREST. (After Penck.)
1, gneiss and granite; 2, Bunter sandstone; 3, Muschelkalk; 4, Keuper; 5, Lias; 6, Dogger, or Oolite; 7, White Jura; 8, Tertiary; 9, Pleistocene; (2 to 7 = Mesozoic strata).

downthrows in opposite directions. As a result of these displacements the Rhenish basin came into existence, while the rock-masses along its margins were pushed up to form the ranges of the Vosges and the Black Forest. The crustal movements referred to appear to have been continued down to post-Tertiary times, and have probably not yet ceased, the frequent earthquakes experienced in the neighbourhood of Darmstadt being perhaps an indication of progressive subsidence along lines of dislocation. It is interesting to note that these crustal movements have been accompanied from time to time by volcanic action. The well-known Kaiserstuhl near Freiburg, for example, is the skeleton of what must have been a very considerable volcano.

The evidence that subsid-

ence in the Rhenish basin has continued into the post-Tertiary period is so striking that it may be briefly referred to here. Deep borings have shown that the Pleistocene deposits in the valley of the Rhine in Hesse occupy a profound hollow, surrounded on all sides by older rocks, the bottom of the basin being 270 feet deeper than the lowest part of its rim at Bingen. These deposits, however, are not lacustrine, but fluviatile. Hence we must infer that fluviatile deposition has kept pace with the crustal movement. As the bottom of the Rhine valley has slowly subsided, the river has flowed on without interruption, continuously filling up the gradually deepening basin with its sediment. This is only another example of the fact that movements of the crust, whether of elevation or depression, have often proceeded so slowly that they have been unable to modify the direction of streams and rivers.

While we recognise the influence of earth-movements in determining the form of the surface in the region under review, it is obvious that much rock-material has been removed. The presence of the Mesozoic strata in the basin of the Rhine shows that these must formerly have extended continuously over the adjacent tracts. Yet they have since been largely denuded away from the higher parts of the Vosges and the Black Forest, so that the underlying crystalline rocks have been laid bare, and now appear at the surface over considerable areas.

When we turn our attention to regions of highly

dislocated rocks, where the crustal displacements are of much greater antiquity than those we have just been considering, the surface-features, we find, have often been so modified by denudation that the position and even the very existence of normal faults can be determined only by close observation. In other cases, however, they give rise to marked features at the surface.

The following section across a portion of the Lanarkshire coal-field is drawn upon a true scale. The section traverses several normal faults, the largest

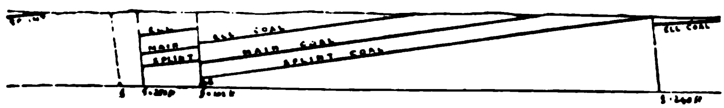

FIG. 67. SECTION OF COAL-MEASURES (ON A TRUE SCALE) NEAR CAMBUSNETHAN, LANARKSHIRE.

being a displacement of 350 feet, yet there is no feature at the surface to indicate its presence.

It is only by studying the geological structure that the existence of such dislocations can be discovered. The strata of the region in question are of much the same consistency throughout, and have therefore yielded equally to the various agents of erosion. Thus all inequalities of surface which may originally have resulted from faulting have been smoothed out. It is doubtful, however, whether such relatively small faults ever did show at the surface. The amount of displacement effected by them usually diminishes upwards, so that the highest coal-seams are hardly dis-

located to such an extent as those which occur at lower levels. Many small faults, indeed, die out upwards altogether. And when we remember that the rocks now exposed at the surface were formerly covered by enormous sheets of strata which have since been removed by denudation, it is not hard to believe that even some of the larger faults of our coal-fields may actually have died out before the original surface of the Carboniferous strata was reached.

Some normal faults, however, are so very extensive—the amount of displacement is so very great—that we must believe they did reach the earth's surface at the time of their formation. Yet where these faults traverse strata having much the same character, they produce no inequalities of level at the surface. A good example is the Tynedale fault of the Newcastle coal-field, which has a downthrow in some places of 1200 feet, and yet its existence is not betrayed by the configuration of the ground. (See Fig. 68, p. 168.)

Great normal faults, however, usually do show more or less conspicuously at the surface. This is due to the fact that by their means areas of soft and hard rock are often brought into juxtaposition. Many examples might be cited from Great Britain. Thus in Scotland the Central Lowlands, consisting largely of relatively soft rocks, have been brought against the harder rocks of the Highlands on the one hand, and those of the Southern Uplands on the other. A

line drawn from Stonehaven in a south-west direction to the Clyde near Helensburgh is at once the geological and geographical boundary of Highlands and Lowlands, while a similar line extending from Dunbar to the coast of Ayrshire near Girvan forms the corresponding boundary of the Lowlands and the

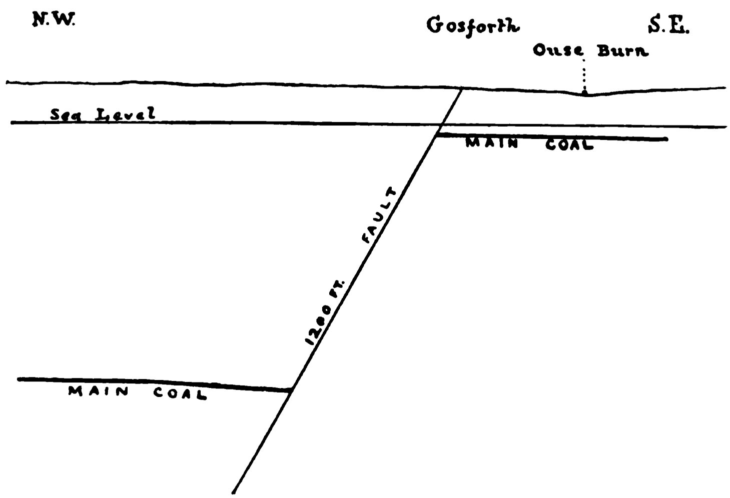

FIG. 68. SECTION ON A TRUE SCALE ACROSS "TYNEDALE FAULT," NEWCASTLE COAL-FIELD.

Southern Uplands. The lines in question are great dislocations, having in places downthrows of 5000 to 6000 feet. But there can be no doubt that the inequalities at the surface are due not so much to the amount of vertical displacement as to the different character of the rocks on opposite sides of the faults. This is well shown by the fact that the disparity of level along a line of dislocation varies with the char-

acter of the rocks which are brought into juxtaposition. Thus, when soft sandstone, as in Strathmore, abut against hard crystalline rocks, the latter rise more or less abruptly above the former—the line of demarcation between Highlands and Lowlands is

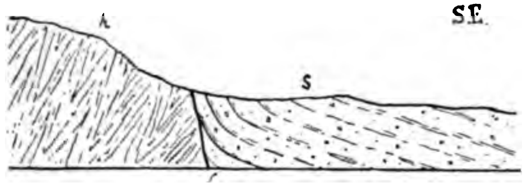

FIG. 69. SECTION ACROSS GREAT FAULT BOUNDING THE HIGHLANDS NEAR BIRNAM, PERTHSHIRE.

h, "hard" grits and shales; *s*, relatively "soft" sandstones, etc. Demarcation between Highlands and Lowlands well marked.

strongly pronounced. But when, as between the valleys of the Earn and the Teith, the hard igneous rocks of the Lowlands are brought against the crystalline schists of the Highlands, the geographical boundary of the two regions is not nearly so well marked—the Highland mountains seem to merge gradually into the Lowland hills. And the same phenomena are conspicuously displayed along the margin of the Lowlands and the Southern Uplands. In a word, it is obvious that while the position of the boundaries that separate the Lowlands from the mountain-areas to north and south has been determined by normal faults, the existing configuration is the result of long-continued and profound denudation.

The accompanying sketch sections (Figs. 69, 70) will serve to illustrate the foregoing remarks.

Normal faults, as we have seen, have often determined the boundaries between lowlands and highlands. Not infrequently, indeed, it can be shown

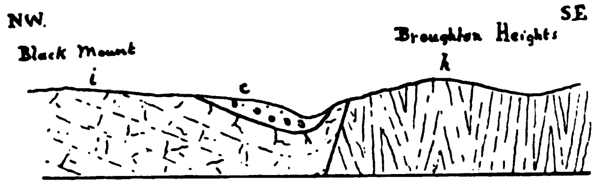

FIG. 70. SECTION ACROSS GREAT FAULT BOUNDING THE SOUTHERN UPLANDS.

h, "hard" greywackés, etc.; *i*, "hard" igneous rocks and overlying conglomerate *c*. Demarcation between Uplands and Lowlands not well marked.

that the dominance of certain mountains is due rather to the sinking down of adjacent low-lying tracts than to bulging up of the crust within the mountain-areas

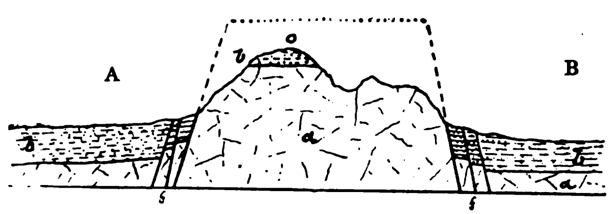

FIG. 71. DIAGRAM SECTION ACROSS HORSTGEBIRGE.

a, granite, gneiss, etc., forming the "Horst"; *b*, stratified rocks of relatively late age, resting upon *a*, dropped down along lines of dislocation *f f*: *o*, outlier of *b*, showing that the strata *b* were formerly continuous between *A* and *B*.

themselves. Such mountains are, of course, bounded by faults, and are known to German geologists as *Horste* or *Rumpfgebirge*, the Harz being a good example. The *Horste* of Middle Europe are composed for the most part of crystalline schists and Palæozoic rocks, more or less highly flexed and disturbed. The

mountains usually rise somewhat suddenly above the surface of the relatively undisturbed and approximately horizontal Mesozoic strata of the adjacent low grounds, and for a long time it was supposed that these strata in the immediate vicinity of the *Horste* were littoral deposits. Such, however, is not the case. They are of relatively deep-water origin, and, before faulting supervened, may have covered much of the high lands which now overlook them. It is obvious, in short, that the *Horste* represent portions of the crust which have maintained their position ; they are mountains which testify to a former higher crustal level ; the surrounding tracts have broken away from them, and dropped to a lower position.

Probably enough has now been advanced to show that normal faults have had no inconsiderable share in determining surface-features. This, as might have been expected, is most conspicuous in regions of recent crustal deformation and fracture, where epigene action has not had time to effect much modification. In cases of very ancient fracture and displacement, however, the surface-features, as we have seen, are very greatly modified, and if well-marked disparity of level is still often met with along lines of dislocation, this is mainly due to the fact that rocks of unequal endurance have been brought into juxtaposition. In a case of very considerable displacement it will usually happen, indeed, that crystalline schists, plutonic rocks, or hard Palæozoic strata will occur upon the high side and relatively softer strata on the low side

of the fault. However prolonged and intense epigene action may have been, such a fault will nevertheless cause a marked feature at the surface, so long as the general surface of the land remains considerably above the base-level. But when the latter is approached denudation will eventually cease on the low side of the fault, while material will continue to be removed from the high side, and the disparity between the two will thus tend gradually to disappear. In short, the irregularities of surface determined by the presence of faults pass through the same cycle of changes as all other kinds of geological structure. Should the base-level remain undisturbed epigene action must eventually reduce every inequality, no matter what its origin may have been. Again, were such a reduced land-surface to be re-elevated and converted into a plateau, the lines of dislocation that happened to separate areas of hard rock from regions of soft rock would once more determine the boundaries between high and low ground. The surface of the soft rocks would be lowered most readily, while the more durable hard rocks would come to form elevations. In a word, the features that obtained before the land was reduced to base-level would, under the influence of denudation, tend to re-appear.

CHAPTER VIII

LAND-FORMS DUE DIRECTLY OR INDIRECTLY TO IGNEOUS ACTION

PLUTONIC AND VOLCANIC ROCKS—DEFORMATION OF SURFACE CAUSED BY INTRUSIONS—LACCOLITHS OF HENRY MOUNTAINS—VOLCANOES, STRUCTURE AND FORM OF—MUD-CONES—GEYSERS—FISSURE-ERUPTIONS — VOLCANIC PLATEAUX — DENUDATION OF VOLCANOES, ETC., AND RESULTING FEATURES.

IN preceding pages we have had frequent occasion to refer to igneous rocks. These, as we have seen, may be broadly grouped under two heads—Plutonic rocks and Volcanic rocks. The former have cooled and solidified at a less or greater depth below the surface; the latter, on the other hand, have been extruded at or near the surface. No hard and fast line, however, can be drawn between these two groups. All plutonic rocks are indeed intrusive—they have solidified below ground; but the same is true of the sheets and dikes which traverse a volcano, and which, along with the bedded lavas and tuffs they traverse, are properly described as of volcanic origin. It will be understood, then, that the term *plutonic* is restricted to intrusive rocks which have consolidated at relatively great depths, while the term *volcanic* includes

all igneous rocks which enter or have entered into the formation of a volcano, or which have evidently proceeded from any focus or foci of eruption.

It is needless to say that we can know nothing by direct observation of the conditions and phenomena which attend the intrusion of deep-seated plutonic rocks. But so many of these have been laid bare by denudation, their composition and their relation to surrounding rock-masses have been so carefully studied, that geologists have learned much concerning igneous action of which but for denudation they must have remained largely ignorant. They have ascertained, for example, that such lavas as rhyolite, andesite, and basalt have their deep-seated equivalents in the plutonic granites, syenites, and gabbros. That is to say, we know that the same molten mass solidifies at great depths as granite or other wholly crystalline rock, and at the surface as rhyolite or other semi-crystalline lava. In short, plutonic rocks and their volcanic equivalents have practically the same chemical composition. An acid lava comes from an acid magma, a basic lava from a basic magma. Hence it is inferred that many plutonic rocks now exposed by denudation may have been the deep-seated sources from which ancient lavas have proceeded. On the other hand, there is reason to believe that many plutonic masses may never have had any such volcanic connections.

But whether or no a given plutonic mass be the deep-seated source of some long-vanished volcano or volcanoes does not concern us here. We have sim-

ply to recognise the fact that its exposure at the surface is the direct result of profound denudation. Whether its intrusion had any effect in deforming the surface we cannot tell. Probably, in cases where none of the material was extruded to the surface by contemporaneous volcanic action, there may have been some bulging up of the ground. Deformation of the crust, in short, may quite well have accompanied the subterranean movements of great masses of molten matter. But so long a time has elapsed since the granites and other highly crystalline plutonic rocks were intruded—so enormous has been the thickness of rock removed from above them—that such intrusion cannot be said to have had any direct effect in the production of existing surface-features. It is quite true that many hills and mountains are composed largely or even exclusively of plutonic rocks;

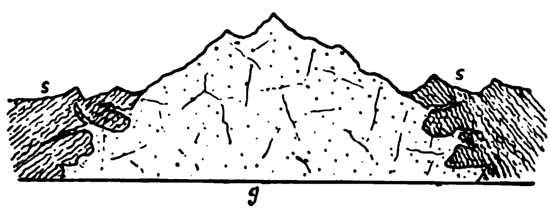

FIG. 72. MOUNTAIN OF GRANITE.

g, granite sending veins into schists, etc., (*s*). The schists have been more readily lowered by erosion than the granite.

but that is simply owing to the fact that these rocks are usually more durable than the rocks through which they rise. When, as not infrequently happens, plutonic masses are of less durable consistency and

construction than the rocks that surround them, the latter invariably dominate and overlook the former. Thus while granite often forms prominent mountains (Fig. 72, p. 175), not infrequently it is found occupying low tracts flanked by mountains of schist, slate, or other rock. (Fig. 73.)

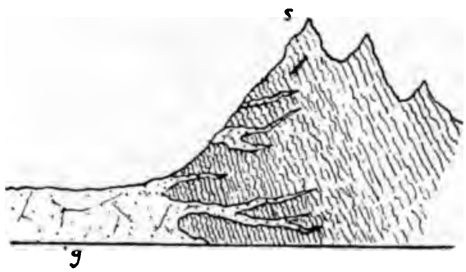

FIG. 73. PLAIN OF GRANITE OVERLOOKED BY MOUNTAINS OF SCHISTS, ETC.
g, granite; *s*, schists, etc. The granite has been more readily lowered by erosion than the surrounding schists.

We must conclude, then, that whatever effect may have been produced at the surface by the intrusion of the more ancient plutonic rocks of England and other countries, such superficial effects, if any, have long since disappeared. The present configuration of the ground occupied by such rocks is wholly the result of epigene action. But when we consider the phenomena of more recent intrusions of igneous rock, we find reason to conclude that these have not only had a direct effect at the surface, but that this effect has not yet in all cases been removed by denudation. The ground has bulged up, and the swelling of the surface is still conspicuous. Among the most re-

markable examples known are the *laccoliths* or laccolites (stone cisterns) of the Henry Mountains (southern Utah), which have been described by Mr. Gilbert. In that region molten rock, instead of ascending to the surface and building up mountains by successive eruptions, has stopped at a lower horizon, insinuated itself between the strata, and opened for itself a chamber by lifting all the superior beds. (See Fig. 74.) Proceeding from a laccolith are in-

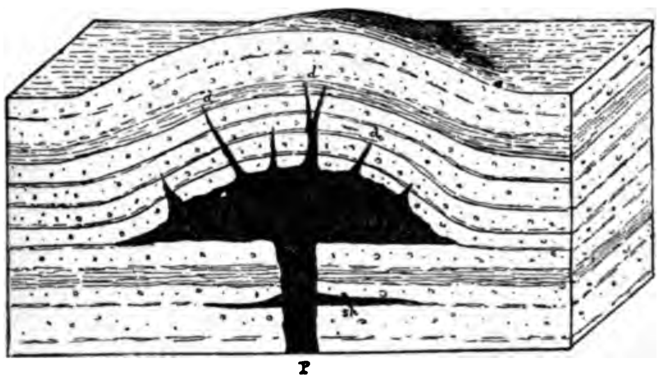

FIG. 74. DIAGRAMMATIC SECTION OF A LACCOLITH SHOWING DOME-SHAPED ELEVATION OF SURFACE ABOVE THE INTRUSIVE ROCK. (After G. K. Gilbert.)
P, pipe or conduit; *sh*, sheet; *d d*, dikes.

trusions of the same kind of igneous rock (trachyte), some of which (*sheets*) have squeezed themselves between adjacent beds, while others (*dikes*) traverse the strata at less or greater angles. These remarkable rocks have been intruded in a great series of strata ranging in age from Carboniferous to Cretaceous, amongst which they are irregularly distributed, some

appearing in the Carboniferous, some in the Jura-Trias, and others in the Cretaceous. From the lowest to the highest laccolith the range is not less than 4000 feet, those which are above not infrequently overlapping those which lie below. "Their horizontal distribution is as irregular as the arrangement of volcanic vents. They occur in clusters, and each cluster is marked by a mountain. In Mount Ellen there are perhaps thirty laccolites; in Mount Holmes there are two; and in Mount Ellsworth one. Mount Pennell and Mount Hillers have each one large and several small ones." The highest of these mountains attains an elevation of over 11,000 feet, rising some 5000 feet above the plateau at its base. The strata of which that plateau is built up are approximately horizontal, and appear at one time to have been covered by some thousands of feet of Tertiary deposits, the nearest remains of which occur at a distance of thirty miles from the Henry Mountains. Mr. Gilbert is of opinion that the laccolites were most probably intruded after the deposition of the Tertiary strata, and before their subsequent removal by erosion.

The whole structure of the Henry Mountains shows that the actual surface was affected by those intrusions, the horizontal strata being arched upwards so as to form dome-shaped elevations, rising prominently above the general level of the plateau. The laccoliths are all of considerable size, the smallest measuring more than half a mile, and the largest about four miles in diameter. The mountains formed by them

consist of a group of five individuals separated by low passes, but having no definite range or trend. The subsequent erosion of these mountains, Mr. Gilbert remarks, has given the utmost variety of exposure to the laccoliths. In some places these are not yet uncovered, and we see only the arching strata which overlie them, the strata being cut across by only a few dikes or traversed by a network of dikes and sheets. In other places denudation has partly bared the laccoliths or even completely exposed them, so that their original form can be seen. In yet other places the bared laccolith itself has been attacked by the elements, and its original form more or less changed. It is even quite possible that occasionally laccoliths may have been entirely demolished, and that some of the truncated dikes now visible at the surface may mark the old fissures or conduits through which such vanished laccoliths were injected.

From the evidence just referred to, it is obvious that intrusions of igneous rock, if of sufficient thickness, are capable of warping the surface, and of forming more or less considerable elevations. But as erosion tends to reduce all such upheavals more or less rapidly, it is only those of relatively recent age that can retain any trace of their original configuration. All masses of intrusive rock of great geological antiquity, which now form hills and mountains, do so in virtue of their greater resistance to the action of epigene agents. They may have arched up the rocks underneath which they formerly lay buried, and so

produced more or less prominent elevations at the surface, but such primeval land-forms have been entirely removed—the features now visible are the direct result of erosion and denudation.

Of true volcanic rocks it is not necessary to say much. Their eruption at and near the surface gives rise to hills and mountains of accumulation, the general aspect and structure of which are sufficiently familiar. The typical volcano is a truncated cone, built up usually of successive lava-flows and sheets of loose ejecta. At the summit is the central cup, or crater, marking the site of the vertical funnel, or throat, through which the various volcanic products find passage to the surface. These are naturally arranged round the focus of eruption in a series of irregular sheets, beds, and heaps, which dip outwards in all directions. It is this disposition of the materials which gives its characteristic form to a volcano. The upper part of the cone inclines at an angle of 30° to 35°, but this steep slope gradually decreases until towards the base the inclination may not exceed 3° or 5°. In a typical volcano, therefore, the internal geological structure and the external configuration coincide—the mountain with its graceful outline is the direct result of subterranean action. It is obvious, however, that the quaquaversal arrangement of the lavas and tuffs is a weak structure. Many cones, it is true, are braced and strengthened by dikes and other protrusions of molten rock, which consolidate in the cracks and fissures that often traverse a volcanic

mountain in all directions. But, although such intrusions may delay, they cannot prevent the ultimate degradation of a volcano which has ceased to be active.

Active and dormant or recently extinct volcanoes differ in form, to some extent, according to the prevalent character of their constituent rocks, and the manner in which these have been heaped up. Some cones consist of cinders, or other fragmental ejecta, with which no lava may be associated. Not infrequently, again, such cones have given vent to one or more lava-flows. From small cinder-cones, showing a single *coulée*, to great volcanoes built up of a multitudinous succession of lavas and sheets of fragmental materials, there are all gradations. The smaller cones are often the products of a single eruption; while the larger cones owe their origin to many successive eruptions, between some of which there may have been prolonged periods of apparently complete repose. The beautiful symmetry of the typical cone is often disturbed. This is due sometimes to the shifting of the central focus of eruption; sometimes to the escape of lava and ejecta from lateral fissures opening on the slopes of the mountain. Not infrequently, also, the symmetry of a growing cone is liable to modification by the action of the prevalent wind, the loose ejecta during an eruption falling in greatest bulk to leeward.

Tuff-cones and cinder-cones range in importance from mere inconsiderable hills to mountains approach-

ing or exceeding 1000 feet in height. In the typical cinder-cone the crater is small in proportion to the size of the volcano ; it is simply an inconsiderable depression at the summit of the cone. Occasionally, however, we meet with large crateral hollows, mostly now occupied by lakes ringed round by merely an insignificant ridge of fragmental materials. Sometimes, indeed, such large hollows show no enveloping ring whatsoever. Extensive craters of this kind are believed to be the result of explosive eruptions, and it is quite possible, or even probable, that their width has been considerably increased by subsequent caving in of the ground. Cinder-cones and tuff-cones vary in form according to the character of their constituent materials. When coarse slags and scoriæ or pumice predominate, the sides of the cone may have an inclination of 35°, or even of 40°. When the materials are not quite so coarse, the angle of slope is not so great ; it diminishes, in short, as the ejecta become more finely divided, so as sometimes not to exceed 15°.

Just as there are cones composed chiefly or exclusively of fragmental materials, so there are volcanoes built up of one or of many successive lava-flows, with which loose ejecta may be very sparingly associated, or even sometimes absent altogether. Lava-cones likewise vary in shape and size according to the nature of their component rocks. Some form abrupt hills of no great height; while others are depressed cones, attaining a great elevation and sloping at a

very small angle, so as to occupy wide tracts. The abrupt cones consist chiefly of the more viscous lavas which have coagulated immediately round the focus of eruption. The depressed cones, on the other hand, are built up of the more liquid lavas, which flow out rapidly, and reach relatively greater distances from the focus of eruption. Not infrequently the cones formed by the outwelling of very viscid lava show no crater—the lava coagulates around and above the vent. In other cases the top of the abrupt dome-shaped cone is blown out by escaping gases, and a crater-shaped hollow is thus formed. The volcanoes of the Hawaiian Islands present the grandest examples of the eruption of liquid lavas. Hawaii itself is made up of five volcanic mountains, ranging in height from some 4000 feet up to nearly 14,000 feet. All these are depressed cones. Mauna Loa (13,675 feet), for example, has a broad, flattened summit, sunk in which is the great cauldron-like crater, some 3½ miles in length by 1½ in width, and 800 feet deep. From the lip of this crater the mountain slopes outwards at an angle of 3°, which gradually increases to 7°, the diameter of the mountain at its base being not less than 30–40 miles.

But composite cones, built up of lava and loose ejecta, are of far more common occurrence than cones composed of lava alone. To this class belong most of the better-known volcanic mountains. Their general characters have already been outlined in the short description we have given of a typical volcano.

It remains to be noted that many composite volcanoes show a cone-in-cone structure. During some paroxysmal eruption the upper portion of a volcano may be destroyed—shattered and blown into fragments. Or, as a result of long-continued activity, the mountain becomes partially eviscerated, and the upper part of the cone eventually caves in, and a vast cauldron is formed, after which a protracted period of repose may ensue. When the volcanic forces again come into action a younger cone, or it may be several such cones, gradually grow up within the walls of the old crater. The younger cones may rise in the middle of the great hollow, or they may be eccentric, as in the case of Vesuvius, which has grown up upon the rim of the large crater of Monte Somma.

Of comparatively little importance from our present point of view are mud-volcanoes. Some of these owe their origin to the escape of steam and hot water through disintegrated and decomposed volcanic materials, either tuff or lava, or both. They are usually of inconsiderable size, many being mere monticles, while others may exceed 100 feet in height. They show craters atop, and have the general form of tuff-cones. Their origin is obvious. The mud is simply flicked out as it bubbles and sputters, and the material thus accumulates round the margins of the cauldron, until a cone is gradually built up. Other so-called mud-volcanoes have really no connection with true volcanic action, but owe their origin to the

continuous or spasmodic escape of various gases, such as marsh-gas, carbonic acid, sulphuretted hydrogen, etc. The mud of which they are chiefly composed is saline, and usually cold. Now and again, however, stones and *débris* may be ejected. These "volcanoes" (variously known as *salses*, *air-volcanoes*, and *maccalubas*) usually form groups of conical hillocks like miniature volcanic cones. Here also may be noted, in passing, the sinter-cones formed by those eruptive fountains of hot water and steam which are known under the general term of *geysers*. When the geyser erupts on level, or approximately level, ground, the sinter tends to assume a dome-shape; when, on the other hand, the springs escape upon a slope, the silicious deposits are not infrequently arranged in successive terraces.

All the volcanic eruptions to which we have been referring have proceeded from isolated foci. Some volcanoes are quite solitary, others occur in irregular groups, while yet others appear at intervals along a given line. These last are obviously connected with great rectilinear or curved dislocations of the earth's crust; not a few of the former, however, apparently indicate the sites of funnels or pipes which have been simply blasted out by the escape of elastic vapours. There is yet another class of volcanic eruptions which have played a prominent part in geological history, although they are not now so common. These are the *fissure* or *massive eruptions*, of which the best examples at the present time are furnished by Iceland.

Lavas, usually of the more liquid kind, well out sometimes simultaneously from more or less numerous vents situated upon lines of fracture, or from the lips of the fissures themselves. Usually such floods and deluges of lava are not accompanied by the discharge of any fragmental materials. Sheet after sheet of molten rock has been discharged in this manner so as to completely bury former land-surfaces, filling up valleys, submerging hills, and eventually building up great plains and plateaux of accumulation. The basalt-plains of Western North America, which occupy a larger area than France and Great Britain, are the products of such massive eruptions, the lavas reaching an average thickness of 2000 feet. The older basalts of Iceland, the Faröe Islands, the Inner Hebrides, and Antrim are the relics of similar vast fissure eruptions. And of like origin are the basaltic plateaux of Abyssinia and the Deccan in India. The volcanic phenomena of the Hawaiian Islands have also much in common with fissure or massive eruptions.

The forms assumed by the materials accumulated at the surface by subterranean action are all more or less distinctive and characteristic. Hills, mountains, plains, and plateaux, which owe their origin directly to volcanic activity, agree in this respect, that their internal structure and external form coincide. Even the most perfectly preserved examples of volcanic accumulation, however, are seldom without some trace of the modifying influence of epigene action. The

shape of a volcanic cone, for example, during its period of growth is subject to modification. Wind affects the distribution of loose ejecta, while rain and torrents sweep down materials, and gullies and ravines furrow the slopes of the mountain. The ravages thus caused continue to be repaired from time to time so long as the volcano remains active. But when its fires die out and the mountain is given over to the undisputed power of the epigene agents, the work of degradation and decay proceeds apace. The rate of this inevitable destruction is influenced by many circumstances—by the nature and structure of the materials, for example, and the character of the climate. Thus, cones built up of loose scoriæ are likely to endure for a longer time than cones composed of fine tuff and hardened mud. Rain falling upon the former is simply absorbed, and consequently no torrents scour and eat their way into the flanks of the cones, while tuff- and mud-cones are more or less rapidly washed down and degraded. Again, a composite volcanic mountain of complicated structure, the product of several closely associated vents, buttressed and braced by great pipes of crystalline rock and an abundant series of larger and smaller dikes, is better able to withstand the assaults of epigene agents than a cone of simpler build. Sooner or later, however, even the strongest volcanic mountain must succumb. Constantly eaten into, sapped, and undermined, it will eventually be levelled.

In regions of extinct volcanoes we may study every

stage in the process of demolition. Isolated cones and groups of cones crumble away, until all the lavas and tuffs ejected from the old vents may have disappeared, and the only evidence of former volcanic action that may remain are the basal portions of the dikes that proceeded from the foci, and the solid cores with which the latter were finally plugged up. (See Fig. 75.) As these cores usually consist of more

FIG. 75. VIEW OF NECKS = CORES OF OLD VOLCANOES. (Powell.)

durable materials than the rocks they pierce, they tend to form somewhat abrupt conical hills. It goes without saying that such extreme cases of denudation are met with only in regions where volcanic action has for a long time been extinct. Excellent exam-

ples on a relatively small scale are furnished by the so-called "Necks" of Scotland, of which the accompanying section (Fig. 76) shows the general phenomena. Similar structures occur in many parts of Europe and North America.

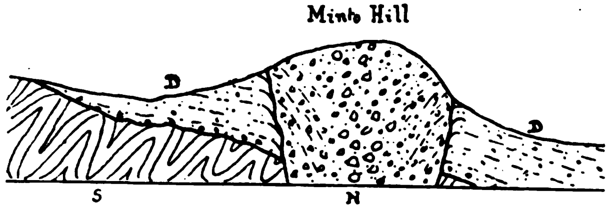

FIG. 76. SECTION OF HIGHLY DENUDED VOLCANO. MINTO HILL, ROXBURGHSHIRE.

N, throat or neck of volcano plugged up with ejectamenta, angular and subangular stones, grit, dust, etc.; *S*, Silurian rocks; *D*, Old Red Sandstone strata.

Frequently the products of great volcanic eruptions of vast geological antiquity have been largely preserved, owing to their subsequent burial under sedimentary accumulations. Many of the hill-ranges of Central Scotland, for example, are built up of lavas and tuffs. These are the relics of volcanoes which came into existence in Palæozoic times, and after erupting molten and fragmental materials for longer or shorter periods, eventually died out, becoming submerged and covered with sedimentary accumulations to depths of several thousand feet. Subsequent elevation of the region brought these sediments under the operation of the agents of erosion, and in time great thicknesses were removed, so that ultimately the ancient volcanic rocks were again laid bare and in their turn exposed to denudation. But if the lat-

ter now form hills, it is simply because they consist for the most part of more durable rock than the formations amongst which they lie. It is needless to say that all trace of their original configuration has disappeared. Indeed that had already vanished before the extinct volcanoes became entombed. Now and again the sites of the old foci of eruption seem to be indicated by bosses and dikes of intrusive rock, but the general form and aspect of the hills are solely the results of erosion, determined and guided by geological structure and the nature and character of the old volcanic materials. They are true hills of circumdenudation. (See Fig. 77.)

The massive or fissure eruptions of former times have in like manner been largely modified by subsequent epigene action. Although some of these belong to a comparatively recent geological period, they have yet been so carved and cut up, that their original plateau-character has become obscured or even lost. Yet there can be no doubt that they formerly existed

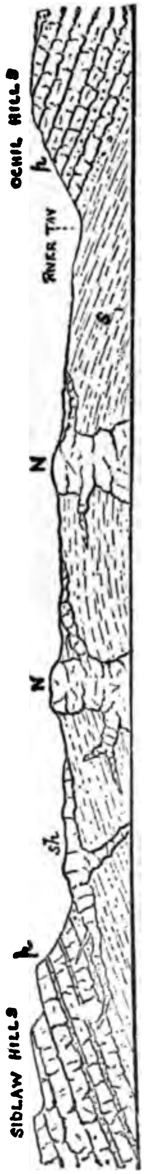

FIG. 77. DIAGRAMMATIC SECTION ACROSS THE VALLEY OF THE TAY, NEAR DUNDEE. *s*, Old Red Sandstone, etc.; *p*, lava-form rocks and interbedded conglomerates, etc.; *sh*, intrusive sheets; N N, necks filled with diabase, etc.

as broad plains and plateaux, occupying many thousands of square miles. The older hills of Iceland, all the Faröe Islands, and the basalt hills of the Inner Hebrides and Antrim are the relics of vast plateaux, which were all probably at one time connected. The general aspect of the hills carved out of such plateaux is well illustrated by the Faröe Islands, to which some reference has been made in Chapter III.

It is believed, as already mentioned, that massive eruptions have proceeded rather from systems of fissures than from separate and individual foci, after the manner of most modern volcanoes of the cone and crater type. During the eruption of the plateau-basalts of Antrim and the Inner Hebrides, molten rock underlay not only those regions, but wide areas beyond, in the north of Ireland and through out central and southern Scotland and the north of England. All these areas are traversed by dikes of basalt, which become more and more abundant as they are followed towards the regions occupied by the basalt-flows. It is from these dikes that the latter appear to have proceeded. From the dikes that are now seen striking across Scotland and the north of England probably no outflow of lava took place ; the fissures up through which the molten rock came did not in those regions reach the surface. They are now exposed simply owing to denudation. Not a few dikes indeed still lie concealed. In the coal-fields these are found cutting across the lower seams, but wedging out before the upper seams are reached.

The larger dikes in central Scotland often form conspicuous objects in a landscape. Owing to the superior durability of the basalt, they rise above the surface of the sedimentary rocks they traverse, and may occasionally be followed for miles, running as they do like great walls or prominent ridges across dale and hill. As examples may be cited two large parallel dikes which may be traced for many miles from Friarton Hill, near Perth, in a westerly direction. Near Dupplin, the more northerly of the two gives rise to a long prominent bank, which is followed for some miles by an old Roman road. In the neighbourhood of Crieff both dikes are equally conspicuous, rising as bold wall-like ridges, the more prominent of the two forming the steep crag upon which Drummond Castle is perched. When dikes cut through rocks as durable as themselves they cease to produce any marked feature at the surface. On the other hand, when the rocks traversed by them are the most resistant, the presence of the dikes is indicated by long trenches or hollows at the surface. Nothing could be so impressive and suggestive of the potency of long-continued erosion than the cropping out of these remarkable dikes. Their intrusion appears to have taken place in Tertiary times, and the great majority of those which occur in the mainland of Britain never actually communicated with the surface at the time of their formation. They cooled and consolidated below ground, yet we now see them laid bare not only in the low grounds and

in valleys, but upon hill-slopes and hill-tops. Obviously hundreds of feet of rock have been removed from the whole land-surface since those dikes were injected.

In fine, then, we conclude that many most conspicuous and characteristic features of the land owe their origin to igneous action. In some places the intrusion of masses of molten rock has produced more or less prominent swelling and bulging at the surface, while the outpouring of volcanic materials has resulted in the formation of hills and mountains, and of plains and plateaux of accumulation. Ere long, however, all such land-forms become modified by epigene action, and more or less completely changed. Intrusive masses formerly deeply buried are eventually exposed, and, owing to the more rapid removal of the rocks through which they rise, may come to form mountains of circumdenudation, while these in their turn tend to be reduced to a base-level. Volcanoes, in like manner, are broken down and crumble away, until it may be the only relics that remain are plugged-up vents, and the dikes proceeding from them, every fragment of the cones having vanished. Or the lavas of former times, having been interbedded with and deeply buried under strata of aqueous formation, may, owing to their superior durability, come to form escarpment-hills and mountains, when the strata originally deposited above them have been removed by denudation. So again volcanic plateaux are dug into by erosion, and pass

through a well-marked cycle of changes. The plateaux are broken up into groups of pyramidal mountains, and these in time are reduced, and may even be entirely replaced by plains of erosion. Thus in lands which have been for long periods of time exposed to erosion, although evidence of former igneous action may abound, and irruptive and eruptive rocks may enter prominently into the formation of the more striking surface-features, the shape of the latter we see is entirely the result of denudation and erosion. If the igneous rocks now form hills and mountains, it is because of their superior durability. Intrusive and effusive rocks alike appear at the surface, and the forms they assume depend chiefly upon the geological structure and mineralogical character of the masses.

CHAPTER IX

INFLUENCE OF ROCK CHARACTER IN THE DETERMINATION OF LAND-FORMS.

JOINTS IN ROCKS AND THE PART THEY PLAY IN DETERMINING SURFACE-FEATURES — TEXTURE AND MINERALOGICAL COMPOSITION OF ROCKS IN RELATION TO WEATHERING—FORMS ASSUMED BY VARIOUS ROCKS.

THE origin of surface-features, as we have now learned, is frequently complex. Only in very few cases can we assert that any prominent feature is the direct result of crustal movement alone. In time all features due to plutonic or subterranean action become more or less modified. We are justified in maintaining that the great mountain-chains of the globe owe their origin indeed to folding and fracturing of the crust; but even the youngest of these has yet been so profoundly modified by epigene action, that the external configuration no longer coincides, save in a general way, with the internal geological structure. Each chain as a whole owes its existence to crustal deformation, but the individual mountains of which it consists are largely monuments of erosion. And so of land-surfaces generally we may say that their more prominent features are the

result of denudation, guided and controlled by geological structure. We cannot study the configuration of the land, however, without perceiving that the relative durability of rocks has also had some share in determining the form of the surface. In regions composed largely of "soft" rocks we may note a general absence of abrupt and broken outlines; the surface even when hilly is usually rounded and gently undulating. It is otherwise when "hard" rocks predominate, the features assumed by these tending to be less smooth and flowing. The surface becomes more diversified still, however, when both soft and hard rocks occur together. In a word, hard rocks at all elevations offer most resistance, while soft rocks more readily succumb to epigene action. We thus arrive at the general conclusion that the form assumed by the land under long-continued erosion and denudation is determined *directly* by the character of the rocks and the mode of their arrangement, and *indirectly*, of course, by igneous action and crustal movements, to which the most striking and conspicuous geological structures are due.

These general conclusions have now been sufficiently illustrated, and we may next consider certain surface-features a little more closely. Rocks, as we have seen, consist roughly of two great classes—those which occur in more or less distinct beds or strata, and those which show no such arrangement, but appear as amorphous masses. The former class is typically represented by sandstones, shales, and limestones, the

latter by granite, syenite, and other eruptive rocks. Most of the bedded rocks are fragmental or clastic; but crystalline rocks, such as the various lavas, not infrequently assume bedded forms. With few exceptions all great amorphous rock-masses are crystalline. There is yet another important group of crystalline rocks—the schists—which to some extent simulate the characteristic structures of clastic rocks. Thus they often show a kind of bedding, and their foliation mimics, as it were, the lamination of shaly strata. The foliation and bedding, however, are commonly more or less puckered and contorted.

Now all rocks are traversed by natural division-planes or joints, and these, in the case of well-bedded strata, are usually disposed at approximately right angles to the planes of bedding. Thus, as we have seen, beds of sandstone, etc., are divided up into somewhat quadrangular or cuboidal blocks. Old lava-flows, in like manner, often show at least two similar sets of vertical joints, and not infrequently these are cut by a third set, disposed at approximately right angles to the others. Not a few bedded igneous rocks and intrusive "sheets," again, assume a more or less columnar aspect, owing to the symmetrical arrangement of the joints. In amorphous masses of crystalline rocks, on the other hand, uniform jointing as a rule is absent. Their division-planes run in various directions, and are often extremely irregular. In some places they may be very closely set, in other places they are far apart.

Thus while bedded strata of all kinds, breaking up along the joints, tend to give rise to rectangular features at the surface, amorphous crystalline rocks, quarried by epigene action, generally yield irregular contours. And the same is the case with the crystalline schists, the jointing of which is as a rule capricious and uncertain.

It is obvious, therefore, that surface-features must be greatly influenced by the character of rock-joints. Apart altogether from other geological structures, joints must largely determine the physiography of the surface. To such an extent is this the case, that it is generally easy to tell at a glance whether any particular mountain is composed of amorphous crystalline rocks, of schists, or of regularly bedded strata. Mountains carved out of horizontal strata tend, as we have seen, to assume pyramidal forms, while in the case of inclined beds erosion and denudation result in the formation of escarpments and dip-slopes. This, however, only holds true when relatively hard beds are intercalated among a series of softer strata. Should the rocks throughout be of much the same consistency no escarpments will be developed, but the whole will wear away equally, and so give rise to a gently undulating surface. Usually, however, a thick series of strata will be found to comprise rocks of various degrees of durability; and in general, therefore, bedded rocks, whether horizontal or inclined, tend to yield rectangular outlines. But when the dip greatly increases, and the strata are more or less vio-

lently contorted, the beds are often crushed and confusedly shattered or jointed, while at the same time the rocks themselves may become metamorphosed, and eventually pass into the condition of schists. Rectangular outlines are thus gradually replaced by the jagged, rough, and abrupt configuration which is so characteristic of slaty and schistose or foliated rocks.

Amongst the crystalline schists rectangular outlines are not common. Now and again, however, when different kinds of schists rapidly alternate in successive sheets or beds, some will almost certainly weather more rapidly than others. The outcrops of the less yielding rocks will thus tend to project; but as jointing is usually irregular and confused, such outcrops seldom show rectangular outlines. Exceptionally, well-marked escarpments may be met with, but the general high dip and contorted character of the rocks forbid such formations. When steep wall-like outcrops of schists occur, they have very often been determined by the presence of normal faults or of thrust-planes. In short, while the foliation and pseudo-bedding of schistose rocks now and again give rise to surface-features which are more characteristic of truly bedded strata, yet such features are apt to be strongly modified by the vagaries of the jointing.

In amorphous crystalline masses, which show neither bedding nor foliation, the character of the joints usually varies with the nature of the rock. In

granite, for example, there are usually three sets of joints, one of which traverses the rock in an approximately horizontal direction, or may have a dip now in one direction, now in another. The vertical joints often cut each other at right angles, but not infrequently they meet at more or less acute angles. In addition to these main joints, however, there are often others. Sometimes the joints are wide apart, and they then enclose large rectangular or rhomboidal blocks. At other times they are set so closely together that the rock when exposed breaks up into a mass of angular *débris*. As the character of the jointing varies in this way within narrow limits, the rock tends to assume broken interrupted contours. On the other hand, when the disposition of the joint-planes is more regular and better defined, the horizontal joints maintaining their direction for some distance, granite not infrequently breaks up as if it were a bedded igneous rock. A mountain-wall so constructed rises in a series of gigantic steps, like tiers of cyclopean masonry, interrupted by entering and re-entering angles. Where the "horizontal" joints are much inclined a corresponding change in the direction of the main rock-ridges and reefs may be observed. Not infrequently, however, the horizontal jointing is obscure and ill-defined or even wanting, and the chief contours of the surface are then determined by the vertical joints alone. Under such conditions the mountain-slope shows irregular vertical or steeply inclined walls, ridges, and but-

PLATE I.

Joints in granite, Glen Eunach, Cairngorm.

tresses, which often run into each other as they are followed upwards, and may eventually taper off to a point. (See Plate I.)

The influence of joints, however, is apt to be greatly obscured by the manner in which rocks themselves disintegrate and crumble down. The sharply angular rock-faces defined by joints are slowly or more rapidly eaten into by epigene action, and the rock exfoliates or crumbles down irregularly according to its character. Indeed, this rotting action has often proceeded very far before the joint-faces are laid bare. When a mass of rock, losing its support, falls away, the new surface exposed has already become to a larger or smaller extent disintegrated and decomposed, so that frost and rain are enabled rapidly to reduce and modify it. Hence the sharp irregular outlines which joints naturally tend to produce are, in the case of such rocks as granite, generally rounded off. Basalt-rocks in like manner often weather readily and become decomposed and disintegrated along planes of jointing, and thus give rise to a somewhat rounded and lumpy configuration. But there is often much diversity of surface displayed by one and the same rock-mass, the basalt in some places weathering rapidly into rounded forms, while in other places, especially where the rock is fine-grained and compact, the sharp angles of the jointing are better preserved. (See Plate II.)

The usually finer-grained rhyolites, trachytes, andesites, and phonolites are not as a rule so readily dis-

integrated as normal granites and basalts. Their joints, moreover, are not only less uniform, but frequently very abundant and closely set. Such rocks, therefore, are readily broken up. Mountains carved out of them usually show sharp crests and peaks, while their slopes are hidden under curtains of angular *débris*, through which ever and anon are protruded reefs, ridges, buttresses, and bastions of such portions of the rock-mass as are less profusely jointed. (See Fig. 78, p. 203.)

In short, we may say that every well-marked rock-type breaks up and weathers in its own way, so that under the influence of denudation each assumes a particular character. We see this even in the case of well-bedded aqueous rocks. Planes of bedding and jointing no doubt are the lines of weakness along which rocks most readily yield, but each individual rock-species weathers after its own fashion—the different kinds of shale, sandstone, conglomerate, and limestone are decomposed, disintegrated, and crumbled down at different rates, and each in a special way, according to its mineralogical composition and state of aggregation. Thus, although a region built up of bedded aqueous rocks may show the same general configuration throughout—horizontal strata giving rise to pyramidal-shaped hills and mountains, while inclined strata of variable consistency present us usually with a series of escarpments and dip-slopes—yet with all this sameness the details of rock-sculpturing may be singularly varied. And the same is

PLATE II.

Weathering of joints in granite, Cairngorm Mountains.

Fig. 78. View of Mesa Verde and the Sierra el Late, Colorado. (Hayden's Report for 1875.)

Table-land in foreground built up of horizontal sandstones and shales (Cretaceous). Mountains in background consist of crystalline igneous rocks (trachytes).

true of the crystalline schists. Mountains composed of such rocks have much the same general configuration. But when viewed in detail they show with every change in the character of the rock some corresponding change in the aspect of the surface. Again, in the case of granite, gabbro, and other massive igneous rocks, all these doubtless break up and produce characteristic configurations. But in each individual case we may note many details of sculpturing which are not the result of jointing, but of variations in the texture, and even in the mineralogical composition of the rock. We may note further that one and the same kind of rock does not necessarily always present quite the same aspect under weathering and erosion. Much will depend on the character of the climate, on the elevation of the region in which it occurs, and on the nature of the surface, whether, for example, that be steeply or gently inclined.

The characteristic forms assumed by rocks are, of course, best seen in places where these are well exposed. In low-lying tracts the rock-surface is usually more or less concealed beneath alluvial deposits and other superficial accumulations of epigene action. It is in river-ravines and along the sea-coast, or better still amongst the mountains, that rock-weathering must be studied. Even at the higher levels, however, the rocks are often largely concealed under their own ruins. Sheets and cones of *débris* extend downwards from the base of every projecting cliff and buttress. Hence in the case of mountains carved out of bedded

rocks, the rectangular outlines tend to become obscured, projecting rock-ledges gradually disappear under piles of *débris*, and a smooth slope may replace in whole or in part the rectangular corbel-steps of the typical pyramid, while steep escarpments may be smoothed off to more or less gentle inclines. In the case of mountains composed of schistose rocks the general steep inclination and contorted character of the bedding and the varied character of the rocks themselves favour the preservation of abrupt and irregular slopes. There is a general absence of horizontal or gently inclined platforms upon which *débris* may come to rest. The great mass of the material loosened and detached by weathering rolls and shoots downwards to the screes accumulating at the base of the mountains. These, as denudation advances, are of course continually extending upwards. But the characteristic configuration of the rocks above the scree-line is maintained, and not obscured, as so frequently happens in the case of horizontal or gently inclined strata. Amorphous igneous masses break up in so diverse a manner, that mountains composed of such often show much variety of feature. The upper limits of the scree-line are very tortuous, here sweeping up almost to the very crest of a mountain, there hugging the base of gaunt cliffs and precipices. Or, when horizontal jointing is well defined, we may have a succession of abrupt ledges breaking the continuity of a scree-slope. When, on the other hand, vertical joints are most pronounced bare

rock-walls and steep ridges rise more or less abruptly above the limits of the depressed scree-line below.

In regions subject to well-marked dry and rainy periods even low grounds and plateaux not infrequently show much bare rock. This is due to the fact that disintegrated rock-material tends to be swept rapidly downwards by heavy torrential rains. Should the land be well clothed with vegetation, the reduction of the surface is much retarded. The rocks may become rotted to great depths, as in Brazil, but the decomposed material remains *in situ*. Where vegetable life in such latitudes is less prolific the surface becomes scorched and dried, and disintegrated rock-material is readily removed when the rainy season comes round. Under these conditions the surface-features, due to epigene action, are usually strongly pronounced. A plateau of granitoid rock, for example, owing to inequalities of structure, texture, and composition, often yields a highly diversified surface; rounded blocks and boulders of all shapes and sizes appear scattered broadcast, while sporadic masses, stacks, cones, tors, crags, and peaks, and irregular winding gullies and depressions, are everywhere encountered. But the same phenomena, if somewhat less prominently developed, are seen again and again in temperate latitudes. The "tors" of Cornwall are in their way as striking as the *kopjes* of Mashonaland. Many other kinds of rock, after long exposure to the weather, present similar fantastic outlines. The "Quadersandstein" of Saxon Switzer-

land, for example, which over considerable areas lies in approximately horizontal strata, has suffered great erosion, the characteristic features of the region being conical hills or pyramids and broad bastions, along the flanks of which the naked rock appears. Thus exposed to weathering, the sandstones yield along the vertical joint-planes and fall away somewhat unequally, and so stacks and columns eventually become separated from the main rock-masses, and often weather into odd and picturesque forms.

The surface-features assumed by limestone are very characteristic, and these, as in the case of all stratified rocks, are determined by bedding and jointing. But the soluble character of limestone causes it to weather in a manner peculiar to itself. Bare surfaces are eaten into, and become irregularly honeycombed and furrowed—the rock, in short, is corroded by the chemical action of rain. Should the ground be steeply inclined, the surface of the limestone shows numerous more or less parallel gutters and trenches, separated by narrow ridges which are frequently sharp and knife-edged. Upon gentler slopes the gutters are less regular, and the ridges are often somewhat rounded; the whole surface, indeed, may be rudely mammillated, and traversed or interrupted by abrupt furrows and smoother depressions. These appearances are most marked when the limestone is pure; when it contains much insoluble matter the characteristic ridges and trenches, rounded humps and hollows, are seldom well developed. It is needless to add that endless modifications

of the surface-forms referred to result from the character of the bedding and jointing, the latter having often determined the direction of the gutters and furrows. The appearances now described (the Karrenfelder of German writers) are not confined to any particular level, but occur at all levels, being most pronounced, however, on high plateaux and in mountain-regions where there is little or no vegetable covering. Excellent examples are met with in the calcareous tracts of the Alps, in the Jura, in the plateaux of the Cevennes, in the Pyrenees, at Gibraltar, and many other places in Europe.

Owing to its solubility, limestone is not only corroded at the actual surface, but joints and fissures are widened by the same solvent action, and thus, in time, underground channels are licked out, and streams and rivers are gradually conducted into subterranean courses. These now become widened and deepened, not only by chemical solution, but by the mechanical action of running water. Thus, in limestone regions, the whole drainage may be directed underground. Considerable streams and rivers plunge suddenly into the depths, and after a longer or shorter course may reappear at the surface, or they may flow on until they make their final escape on the floor of the sea. The surface of a limestone country is often drilled by more or less vertical holes and pipes of variable width, which communicate directly with subterranean streams and rivers. These pipes are, no doubt, in many cases, licked out by meteoric water, but not infrequently

they are caused by the collapse of the undermined rocks. Owing to various causes, engulfed streams now and again abandon their courses, and work their way to lower levels, and in course of time such abandoned channels may become disclosed by the falling-in of the roof, or by the more gradual denudation and truncation of the rock by surface-action. Hence, in regions built up of calcareous rocks, caves are of common occurrence, many of them being of large dimensions, and often branching in all directions.

Caves and other hollows are not infrequently worked out by weathering in many other kinds of rocks, but in no case do they attain the size of those which we so commonly encounter in areas occupied by limestone, as will be shown in a succeeding chapter.

We need not, however, enter into further detail as regards the characteristic weathering of particular rocks. It is enough for our purpose to recognise the fact that composition and texture play no unimportant part in determining the aspect assumed by rocks under denudation. In preceding pages we have discussed the origin of the salient features of a land-surface. Looked at broadly, it is obvious that the more elevated and more depressed areas owe their existence primarily to movements of the earth's crust. Thus all the great mountain-tracts and plateaux of Europe may be looked upon as regions of relative uplift, while the broad low grounds above which they rise may be described in general terms as regions of relative depression. In a word, the larger features of

the land have been blocked out by subterranean action, they are the result of crustal deformation. Viewed from a nearer standpoint, however, we recognise that every feature due to deformation has been more or less profoundly modified by denudation, guided and determined by the geological structure and relative durability of the rocks. Approaching still nearer, we see how each particular kind of rock wears away in some particular and characteristic fashion, so that surface-features vary infinitely in detail quite independently of the geological structure. Thus the part played by subterranean action is merely to provide the rough block which the epigene agents subsequently sculpture into shape. With few exceptions, the land-features that now meet our eye are the direct result of erosion and accumulation, the modifying influence of which is always more or less conspicuous even in cases of recent crustal deformation.

Now if it be true that the character of a land-surface is determined by geological structure and the nature of the rocks, we should expect to meet with very considerable diversity of configuration in regions built up of many varieties of rock arranged in many different ways. And such undoubtedly is the case; but it is less true of temperate and northern regions than of more southerly latitudes. Not that the influence of rock-structure is ever quite lost even in the former, but it is often obscured. In the contours of the higher Alps, for example, it is conspicuous enough, but the lower mountain-slopes not infre-

quently fail to show it, or show it much less plainly. Further north, as in our country and in Scandinavia, undulating and flowing configurations prevail amongst the mountains. Broken and serrated outlines are seldom seen, and usually only at the higher elevations. Mountains built up of bedded rocks, of schists, of massive igneous rocks, are not so strongly differentiated as similar mountain-masses are in more southern lands. It is only when they are looked at more closely that the influence of geological structure and petrographical character becomes apparent. Everywhere, however, we find that this influence has been more or less interfered with; mountains which, under the ordinary action of the atmosphere, must have assumed serrated crests and peaks, appear instead with rounded, smoothed, and softened outlines; projecting buttresses, reefs, and ridges have lost much of their angularity, and escarpments likewise are frequently bevelled off.

These remarkable modifications of the surface are due to glaciation. There is no reason to doubt that before the advent of the Ice Age rock character and geological structure were as strongly expressed in the configuration of our hills and valleys as they are now in regions which have never experienced glaciation. Indeed, so long a time has elapsed since the disappearance of our ice-fields and glaciers, that the smoothed and rounded surfaces are again breaking up, and the more irregular and angular contours and outlines which obtained in preglacial ages are thus in process of gradual restoration.

CHAPTER X

LAND-FORMS MODIFIED BY GLACIAL ACTION

GEOLOGICAL ACTION OF EXISTING GLACIERS—EVIDENCE OF EROSION—ORIGIN OF THE GROUND-MORAINE: ITS INDEPENDENCE OF SURFACE-MORAINES—INFRAGLACIAL SMOOTHING AND POLISHING, CRUSHING, SHATTERING, AND PLUCKING—GEOLOGICAL ACTION OF PREHISTORIC GLACIERS—GENERAL EVIDENCE SUPPLIED BY ANCIENT GLACIERS OF THE ALPS.

AT the close of the last chapter reference was made to the fact that the surface-features of certain regions have been modified by subsequent glacial action. This action, as we have indicated, tends to efface or obscure the characteristic forms assumed by rock-masses under the influence of weathering. In other words, ice is an eroding agent, but it works in a different way from the ordinary epigene agents. While the latter tend to produce manifold irregularities of the surface, and to develop angular outlines for the most part, the former tends, on the other hand, to smooth away inequalities and to replace angular outlines with rounded contours. It is demonstrable, therefore, that ice is an eroding agent, but some geologists have doubted whether it is very effective, and are of the opinion that the utmost it can do is to

smooth and abrade to a very limited extent. As it is important, from our present point of view, that we should clearly understand this question of glacial erosion, we may consider the evidence in some little detail.

For this purpose we may approach the subject much in the same way as a geologist would do were he endeavouring to prove for the first time that rivers are potent agents of erosion. Doubtless, in such a case, his first care would be to describe the work done by existing rivers; thereafter he would depict the character and attempt to set forth the precise origin of alluvial terraces, plains, and deltas; and, finally, he would adduce evidence to prove that all such formations are products of erosion, and that by the gradual removal of such products valleys have been originated or deepened. In like manner we shall consider first the character of existing glacial action; then we shall inquire into the nature and origin of ancient glacial accumulations; and finally we shall show how these last are evidence of extensive glacial erosion, and how, by their removal, valleys have been widened and deepened, and rock-basins of particular kinds have been formed.

1. *The geological action of existing glaciers.*—The most obvious work performed by an Alpine glacier is that of transport and accumulation. The wreck of the adjacent mountains, strewn upon its surface, is continually carried forward, and eventually heaped up in the form of terminal moraines. The infragla-

cial *débris* extruded at the lower end of the ice-flow bears, usually, a very small proportion to the supply of rock-rubbish travelling at the surface. This, however, is not invariably the case, even in the Alps. Not infrequently small "summit glaciers," lying upon mountain-slopes, bear no superficial detritus, while infraglacial *débris*, nevertheless, is constantly being extruded at their lower ends. Thus the small Stampfl-kees Glacier (Zillerthal), overlooked by hardly any exposed rock-surfaces, and consequently carrying little or no superficial rock-rubbish, yet exhibits at its terminal front a bottom- or ground-moraine some ten or fifteen feet thick. But that which is the exception in Alpine lands is the rule in Arctic regions. The tongues of ice protruding from the vast *mer de glace* of Greenland are almost entirely free from the superficial *débris*, and yet they eject ground-moraine in abundance. The same, as we shall see presently, is the case with most of the Norwegian glaciers. It is obvious, therefore, that the relative importance of ground-moraine, as a product of glacial action, is really greater than a glance at the phenomena of any ordinary Alpine glacier would at first lead one to suppose.

The general nature of Alpine ground-moraine is well known. It consists simply of an aggregate of rock-fragments, grit, sand, and mud or clay, often frozen or pressed together, and so included in the lower or basal portion of the glacier. Many of the stones are subangular and blunted, and striated, smoothed, or polished on one or more sides. No

one doubts that this material has travelled underneath, and partly enclosed in the ice-flow, and that the rock-surface over which it has been carried is abraded, smoothed, and polished by its filing action. Everyone, in short, admits that some degree of erosion is the result of glacial action. Were that action entirely confined to mere abrasion and smoothing of rock-surfaces, it yet could hardly be considered insignificant. The fine powder or flour of rock which renders all glacial rivers turbid, shows that glacial grinding is really of great importance. It has been computed, for example, that the river extending from Aar Glacier carries away daily 280 tons of solid matter in suspension. Again, the Justedal Glacier, draining an ice-field 820 square miles in extent, discharges in a summer day 1968 tons of sediment. This is in excess of the average daily discharge during the year, which Helland estimates at 180 million kilogrammes. To this should be added the mineral matter carried in solution, amounting to 13 million kilogrammes, so that solid and dissolved materials taken together come up to 189,950 tons. This would form a mass equal to 90,252 cubic yards. According to the same geologist, the Vatnajökull (Iceland), draining an ice-field ten times larger than that of the Justedal, discharges annually 14,763,000 tons of sediment—an amount equal to 7,194,000 cubic yards of rock. Thus, even if a glacier does no more than abrade and smooth its bed, the amount of rock ground into powder is neither insignificant nor unimportant.

But is this all the erosion that a glacier accomplishes? What about the *débris* of its ground-moraine —whence is that derived? Professor Heim and others maintain that in the case of a large number of glaciers (Alps, Himalaya, New Zealand) infraglacial detritus comes chiefly from superficial sources. Overlying morainic rubbish, it is supposed, finds its way through crevasses to the bottom of the ice. Now there can be no doubt that surface-moraines are frequently engulfed in crevasses; but then the rock-rubbish engulfed in this way sooner or later reappears at the surface of the glacier further down the valley. Obviously in such cases the *débris* does not descend to the bottom of the glacier, but is simply engorged at some distance from the surface, and again becomes exposed, owing to the curving upwards of the lines or planes of flow and the ablation of the surface. If crevasses penetrated the whole thickness of a glacier, doubtless *débris* plunging into them might well reach the bottom of the ice, and be included as ground-moraine. But the plasticity of ice necessarily limits the depths to which a crevasse can extend. The larger glaciers, according to Heim, are never penetrated to the bottom by crevasses, which when not kept open and deepened by ablation do not exceed a depth of 100–150 metres. Superficially carried rock-rubbish, therefore, can reach the bottom of a moderately thick glacier only along the margin, where the crevasses open to the rock-head. Here and there, perhaps, *débris* may occasionally descend

by *moulins;* but as a rule the bed of such a glacier can receive only a very meagre supply of rock-fragments from above. And if this be the case with the relatively small glaciers of the Alps, it must be the same in a more marked degree with those of high northern and Arctic lands.

Reference has already been made to the fact that even in the Alps certain summit-glaciers are so placed that no *débris* is showered upon them, and yet these glaciers extrude more or less conspicuous ground-moraines. In a word, the existence of ground-moraines does not depend upon the presence of superficial moraines. The latter are not infrequently wanting; the former, on the contrary, never are. This is well seen in the case of the Norwegian glaciers, which, as compared with those of the Alps, might be described as almost devoid of surface-*débris*. Nevertheless, ground-moraines are always in evidence, appearing not only under the tongue-like glaciers which protrude from the plateau ice-fields, but at the base of the more or less steep walls in which those ice-fields usually terminate.

The great development of superficial moraines in the Alps as contrasted with their meagre appearance in Scandinavia is easily explained. In the former region we have a complicated series of mountain-groups and chains, the crests of which overlook profound cirque-like depressions. It is in these broad and deep troughs and basins that snows accumulate to form the reservoirs from which glaciers flow.

Even at its very source, therefore, an Alpine glacier has rock-*débris* supplied to it from above, and as it passes down its mountain-valley frost and avalanches keep up a constant bombardment, so that the farther it flows the greater becomes the amount of detritus eventually piled up in its terminal moraines. Norway, on the other hand, is a lofty plateau, more or less deeply trenched by fiords and valleys. The snows, therefore, accumulate upon a wide and relatively flat or undulating surface, not dominated by peaks or ridges. In the central part of a Norwegian snow-field the surface is more or less continuous, and seldom interrupted by crevasses. Now and again, however, these are encountered, and their walls show stratified *névé* above graduating downwards into compact ice. Towards the margin of such an ice-field crevasses become more frequent, and in these snow and *névé* are seen gradually thinning-off as the terminal wall is approached, until at last the blue ice is wholly exposed. In short, the Scandinavian plateau supports true ice-sheets, comparable in all respects, save as regards their extent, to the great "inland ice" of Greenland. In places, longer or shorter tongues of ice project from the ice-sheet into valleys; in other places, where no valleys are present, the sheet simply terminates in a continuous ice-wall.

Such being the character of the Scandinavian ice-fields, we need not wonder at the absence of superficial moraines. No mountains overlook the plateaux; it is only when the ice creeps outwards into valleys

that it is liable to have rock-rubbish dumped on its surface. Moreover, the course of such valley-glaciers is so short as a rule, and their rate of flow so comparatively rapid, that conspicuous lateral moraines cannot be accumulated. It is further noteworthy that Norwegian glaciers do not form prominent terminal moraines, and these are composed chiefly of water-worn gravel and blunted and subangular stones. Sharply angular blocks and fragments do not predominate as in the end-moraines of Alpine glaciers. In a word, the Norwegian terminal moraines appear to consist mainly of infraglacial and fluvio-glacial detritus, which the ice builds up into low mounds and ridges. But if superficial moraines are sparingly developed, the same is not the case with ground-moraines. These are seen not only under the glacier-tongues in valleys, but they are conspicuous likewise under the bordering ice-walls of the plateau-sheets. Everywhere, also, from the margin of these sheets, as from the valley-glaciers, flow streams and torrents of turbid water.

The phenomena exhibited by the Scandinavian ice-fields are exemplified on a much larger scale in Greenland. There, as in Norway, superficial moraines are entirely wanting, except where the ice-sheet protrudes long tongues into mountain-valleys and fiords. Where the ice-sheet terminates upon land ground-moraines are conspicuous. Nansen, for example, tells us that at Austmannatjern, where he left the inland ice after his famous traverse, enormous accumulations of mo-

raine were seen. These were of true infraglacial origin, consisting largely of blunted and striated stones, which could only have been transported by the ice as ground-moraine. No *Nunatakkr* occurred within the *mer de glace* near this place, and not a vestige of surface-moraine was visible. Dr. Hoist, Dr. Drygalski, and others have referred to the appearance of ground-moraines in Greenland, and the phenomena in question have also been described by Professor Chamberlin. The latter shows that the tongues of ice proceeding from the local ice-caps and from the great inland ice are crowded towards their base with ground-moraine, the lower strata of the ice for a thickness of 50 to 70 feet above the bottom showing layers and irregular sheets of clay, mud, sand, stones, and boulders, all of which are of infraglacial origin, while the upper and much thicker mass of ice is free from such inclusions. It is not necessary to enter into greater detail, but it may be added that in Greenland as in Norway turbid water escapes in large volume from the "inland ice."

Reflecting upon the facts thus briefly recapitulated, we must conclude that glaciers are powerful agents of erosion. Not only do they grind, smooth, and polish rock-surfaces, as everyone admits, but they also quarry their beds. The stones and boulders of the ground-moraines are derived directly from below by the ice itself. In the case of Alpine glaciers, no doubt *débris* may occasionally be introduced to the ground-moraine from above; but this descent of superficial detritus

cannot take place in the plateau-sheets of Scandinavia, nor in the local ice-caps of the great "inland ice" of Greenland. In some way or other, rocks underlying a glacier are liable to disruption and displacement; and such, we cannot doubt, is the chief source of the stones and grit and clay of ground-moraines generally. There is direct evidence, indeed, to show that glaciers not only abrade and smooth, but rupture the rocks over which they flow. Professor Heim refers to an observation of Von Escher on the Zmutt Glacier, underneath which were seen projecting reefs of schist glaciated atop, which had been fractured and sundered by the glacier. Again, Professor Simony has described the appearance presented on the bed of one of the Dachstein Glaciers (Karls-Eisfeld) during the temporary retreat of the ice. What struck him most was not so much the smoothed and polished surfaces as the broken and disrupted masses, the shattering being most marked in places where the rock-ledges faced the direction of the ice-flow. The prevailing character of the erosion, Professor Simony remarks, is that of a continuous rock-shattering. On the north side of the glacier, where the surface had become depressed for 40 to 60 feet, the exposed rocks showed polishing in only a few places, glacial pressure having resulted rather in a wholesale superficial shattering, and in the production of a rubble of angular fragments.

Similar phenomena have been observed by MM. Penck, Brückner, and Baltzer at the Uebergossenen

Alm. During the past thirty years this glacier has retreated for two or three hundred yards. Its deserted bed is traversed by a belt of hornblende-slate, which, like the adjacent rock-masses, is well glaciated and sprinkled with large striated blocks of gneiss. In some places, however, the hornblende-slate, after having been smoothed and polished, has been broken up, and *débris*, consisting of smaller and larger fragments and blocks, *polished on one side only*, are found incorporated in ground-moraine a little further down. This is a clear case of infraglacial quarrying. Another good opportunity of studying the results of modern glacial action has been afforded by the retreat of the Lower Grindelwald Glacier. The lowering of its surface has exposed two rock-terraces. One of these is well glaciated, showing *roches moutonnées* with conspicuous *Stoss* and *Lee-Seiten*. Between the mammillated rocks stretch several shallow rock-basins, some of them being filled with water. One of these, according to Professor Penck, measured 26 feet in breadth, 42 feet in length, and 3½ feet in depth, and was smooth and ice-worn from end to end. Both terraces are trenched by the deep gully of the Lütschine, the upper portions of the rocky walls being conspicuously striated and fluted, while here and there they present the shattered surfaces which are equally characteristic of glacial action.

Professor Brückner has in like manner described the broken and ruptured rocks and smoothed surfaces which appear side by side upon the bed of a glacier.

Thus at the Mazellferner he saw resting upon the jagged projecting out-crops of certain rocks a block, many cubic metres in size, enclosed in ground-moraine, along with which it had travelled over the cracked and shattered rock-ledges. The ground-moraine was squeezed in between the disjointed masses. In another place, where the bed-rock was well smoothed and striated, he observed an irregular rough cavity or hollow, from which a slab of rock had evidently been extracted. In the recently deserted beds of the Obersalzbachkees (Hohe Tauern) and the Hornkees (Zillerthal) he noticed that the rocks were jointed in a direction approximately parallel to their upper surface—a structure which has favoured their rupture and displacement. Here and there, in the midst of a well smoothed area, rough cavities indicated whence slabs had been removed; and now and again the detached fragments themselves were detected. Many such loose slabs were observed by the same geologist on the bed of the Stampflkees. On one side they exhibited the parallel striation characteristic of rock which has been glaciated *in situ*, while the other sides were rough and irregular, and showed no trace of abrasion. That fragments of this character are not more frequently extruded at the lower end of a glacier is readily understood when we remember that they could not travel far below ice without losing their rough surfaces, and becoming more or less glaciated all over.

Professor Chamberlin has recorded the occurrence

of similar phenomena in connection with some of the large tongues of ice which are protruded from the great "inland ice" of Greenland. He says: "The rubbing of the glacier (Bowdoin Glacier) against the shoulders of rock projecting from the side of the valley gave opportunity for observing some of the special phenomena of such situations. At one point the process of 'plucking' was well indicated (though not actually observed) on the lee-slope of a spur of gneissoid rock. Blocks ranging up to three or four feet in width and length, and one or two feet in thickness had been detached in considerable numbers. The process involved much breaking and bruising with relatively little wear. Corners and angles were broken off, and heavy bruise marks were observed both on the blocks and on the sides and edges of the cavities from which they had been removed. At some points considerable crushed rock was observed. On the other hand, systematic grooves and striæ were not abundant nor pronounced. The dynamic impression given was that of a forceful tearing out of blocks by the action of a relatively rigid agency, which did not press the blocks hard upon the lee-slope after their removal."

It is clear, then, that under existing glaciers and ice-fields rocks are sometimes smoothed and polished, sometimes crushed and shattered. The pressure of the ice tends to disrupt rock-masses, which yield or resist according to their character and structure, and fragments detached must often serve as wedges to

dislocate and detach others. Nor can it be doubted that the rocky bed of a glacier is also attacked by frost. The constant outflow of water shows that infraglacial melting goes on all the year round. The temperature at the bottom of the ice oscillates about the freezing-point, and as a glacier flows on its way thawing and freezing must be continually taking place. In this way joints are no doubt opened, rock-masses loosened, and larger and smaller fragments become more readily plucked and dragged out of place.

We cannot, therefore, hesitate to conclude that ice in motion, whether in the form of glaciers or of ice-caps, is a powerful agent of erosion. It not only abrades and smooths, but breaks up and quarries the rocks over which it flows, and the *débris* thus obtained constitutes the true ground-moraine.

2. *Geological action of prehistoric glaciers.* Geologists rightly insist upon the potency of river-erosion. The study of modern denudation has quite convinced them that valleys can be and have been excavated by running water. In proof of this they point not only to the present action of rivers—to the rate of transport of sediment—but to the immense accumulations formed by river-action in prehistoric times. The broad alluvial plains of river-valleys, the great deltas which encroach upon the sea, the wide stretches of flat lands occupying the sites of silted-up lakes, are all cited as evidence of the potency of running water as a producer and transporter of sediment. So in like manner the glacialist appeals to far-ex-

tended accumulations of ground-moraines as proof of the efficiency of flowing ice as an agent of erosion and transport.

The study of modern glacial action is carried on under certain obvious disadvantages. The bed of a glacier is concealed from our view. Now and again we may get a peep under the ice; or, better still, we may have the opportunity of examining the ground from which a glacier has temporarily retired. But the portions of a glacier's bed thus at times exposed are not those where erosive action is most intense. A glacier thins away towards its extremity, and the rate of motion at the same time diminishes, so that pressure and erosion must decrease with the attenuation of the ice. To such an extent is this the case, that the snout of a glacier deploying upon a relatively flat surface often rests upon its terminal moraines, or even overrides the fluvio-glacial gravels spread out in front of it. Such facts have led some observers to conclude that glaciers do not erode at all, and did the facts referred to stand alone there would be some justification for that conclusion. It should be remembered, however, that were observers of river-action to confine attention to the broad plain-track—to the region known as the "base-level of erosion"—they would no doubt readily come to the conclusion that running water transports and deposits sediment; but, by following the process of reasoning just alluded to, they might also infer that rivers are incapable of erosion. Were the beds of existing

glaciers as open to investigation as the channels of rivers, we should probably hear little about the feeble erosive action of ice. But although we cannot make direct observations underneath the central and thicker portions of a glacier, we can yet examine great valleys and broad lowland regions which have been formerly subjected to intense glaciation. And the evidence of effective glacial erosion there displayed is too clear to be wholly misunderstood. Let us then consider the general results which have been obtained by the careful investigation of certain well known glaciated regions—the Alpine lands of Central Europe.

At the climax of the Glacial Period the snow-line in the Alps appears to have been upon an average some 4700 feet lower than now. Viewed from the north, the mountains must at that time have presented the appearance of a great ice-field, broken here and there by *Nunatakkr*—the protruding peaks of the dominant elevations of the secondary ranges, and bounded on the south by the snow-clad ridges of the Central Chain. In a word, so thick was the ice in the valleys that as the glaciers made their way to the low grounds they frequently coalesced or became confluent across intervening mountain-ridges. Under such conditions it is obvious that the formation and accumulation of superficial moraines must have been relatively limited. The area buried under *névé* and ice was greatly in excess of that which remained uncovered. If it be true, therefore, that ground-moraines consist chiefly of rock-*débris* derived from

superficial sources, those of the Glacial Period should be of little importance. The very reverse, however, is the case. The ground-moraines assume an enormous development, their dimensions being in direct proportion to the size of the ice-flows. The larger the body of ice, the greater the mass of ground-moraine.

It must be admitted, therefore, that the materials of the old ground-moraine cannot have been derived from superficial sources. Some have suggested, however, that the accumulations in question consist to a large extent of the products of weathering, of torrential and fluviatile action, which had gathered over the mountain-slopes and in the valleys before the advent of the Glacial Period. There is no reason to believe, however, that rock-rubbish throughout the Alpine lands attained a greater development at the beginning of the Ice Age than it does now. The old snow-fields and glaciers doubtless gradually extended as the temperature fell. As the depression of the snow-line continued, rock-rubbish would accumulate abundantly, just as at present, in every valley occupied by a glacier. For a long time, too, superficial moraines would assume a relatively great importance, so that large terminal moraines would mark every pause in the progress of the ice-flows. But as the glaciers thickened in the valleys, and more and more bare rock disappeared below the ice, the supply of detritus from above would become gradually limited, until in many places, as in the region of the secondary ranges, it practically ceased altogether. Were a glacial period

to supervene at present, each individual glacier would begin to advance, and as it progressed the zone of most active rock-shattering by frost would descend with it to lower and lower levels. But at each step in its advance the glacier would encounter no greater accumulations of rock-rubbish than had all along gathered in its neighbourhood. In short, as Dr. Böhm remarks, weathering would proceed no more rapidly in front of one of the enormous glaciers of the Ice Age than it does now in the vicinity of existing glaciers. "When the Inn Glacier," he says, "had advanced as far as Innsbruck, it would enter no zone of more active rock-shattering than is met with to-day in front of the glaciers of the Oetzthal." It is obvious, therefore, that if the glaciers of the Ice Age derived their subglacial detritus either from above or from frost-riven *débris* and superficial deposits lying in their path, their ground-moraines could not at any one place have attained a greater thickness than those of existing Alpine glaciers; and yet, as is well known, the old ground-moraines reach an astonishing thickness, their bulk being in direct proportion to the size of the former ice-flows.

One may readily exaggerate the importance of the rock-rubbish which is almost everywhere conspicuous in the Alps. The enormous screes of angular blocks and *débris* which shoot down from cliff and buttress contain prodigious quantities of materials. Here, we are apt to think, is sufficient loose material wherewith to form ground-moraines as thick and extensive

as those of the Glacial Period. But is this actually the case? If all the *débris* in question could be lifted and equally distributed over the Alpine lands it would certainly not suffice to raise the general surface of those lands by more than a few feet or yards. The old morainic accumulations, on the other hand, could they be replaced, would add considerably to the average height of the surface. Professor Penck has shown, for example, that the morainic accumulations of the Isar Glacier average a thickness of 20 metres, and cover an area of some 1800 square kilometres. They have been derived from an area 2800 square kilometres in extent. Could they be restored, therefore, they would raise the general surface by about 13 metres. In other words, an area of 1081 square miles has been lowered by some 41 feet. In Dr. Penck's estimate only the morainic matter has been considered, the equally great mass of fluvio-glacial gravels (consisting almost exclusively of remodified infraglacial detritus) has been entirely neglected. Further, we must remember that during the formation of the moraines and fluvio-glacial gravel, enormous quantities of the fine flour of rocks—the result of glacial grinding—must have been carried away in suspension, and deposited in regions far beyond the glaciated areas.

Such considerations as these show that the old morainic accumulations cannot consist merely of the superficial rock-rubbish which the old glaciers found ready to hand, and swept out as they advanced. All such loose accumulations, after excessive glacial con-

ditions had supervened, must erelong have become exhausted, and can form only a small proportion of the ancient ground-moraines. Whence, then, was the great bulk of the material derived? Surely from infraglacial sources, as the direct result of glacial erosion. The immense ice-flows of the Glacial Period must at an early stage have completed the removal of preglacial detritus—none of that detritus can now linger underneath any existing glacier, either in the Alps or in Norway. Yet, as we have seen, ground-moraines are forming at present in both regions. In the Alps, according to Professor Heim and others, the ground-moraines are fed from the surface, but this can be true to only a very limited extent. The plateau ice-sheets of Norway carry no superficial detritus, and their ground-moraines are, therefore, supposed by some to represent the rock-rubbish which gathered over the Scandinavian heights in preglacial times! A vast ice-sheet, as we know, overflowed those regions during the Glacial Period, and buried the low grounds to great depths under the detritus which it carried outwards from the mountains, and yet we are to believe that much loose rock-rubbish of preglacial age still remains to be removed from the continuously ice-covered plateaux of Norway! Must we likewise believe that the "inland ice" of Greenland, which has probably persisted since Pliocene times, has not yet succeeded in removing the products of subaërial weathering, which came into existence before glacial conditions had supervened in Arctic regions?

CHAPTER XI

LAND-FORMS MODIFIED BY GLACIAL ACTION

(Continued)

FORMER GLACIAL CONDITIONS OF NORTHERN EUROPE—EXTENT OF THE OLD INLAND ICE—GENERAL CHARACTER OF BOULDER-CLAY—CENTRAL REGION OF GLACIAL EROSION AND PERIPHERAL AREA OF GLACIAL ACCUMULATION—FLUVIO-GLACIAL DEPOSITS—LOESS, ORIGIN OF ITS MATERIALS—GLACIATION OF NORTH AMERICA—MODIFICATIONS OF SURFACE PRODUCED BY GLACIAL ACTION.

IF a study of the glacial and fluvio-glacial deposits of the Alpine lands leaves us in no doubt as to the efficiency of glacial erosion, an investigation of the similar accumulations of Northern Europe and North America is even more convincing. The boulder-clays of those wide regions are true ground-moraines, recalling in every particular the ground-moraines of the Alpine lands. At the climax of the Glacial Period a great ice-sheet covered all Northern and North-western Europe, extending east from the British area to the Timan mountains, and south to the German ranges. The ice-sheet thus occupied an area of 2,500,000 square miles or thereabout in extent. Above the surface of this inland ice peered some of

the loftier mountain-tops of Scandinavia, and a few *Nunatakkr* in the British Islands. In the low grounds of Scotland the sheet could hardly have averaged less than 2500 to 3000 feet in thickness. In some of the Norwegian fiords it exceeded 5500 feet. Taking the elevation of the ice-shed in Scandinavia as 7000 feet, and the height reached by the ice-front upon the northern slopes of the mountains of Germany as 1350 feet, we get a thickness for the ice-sheet in South Sweden of 2900 feet, of 2500 feet in Denmark, and of 1300 feet or thereabout in the neighbourhood of Berlin.

It is obviously impossible that the ground-moraines of an ice-sheet of such dimensions could have been derived or even supplemented to any extent from superficial sources. The boulder-clays are the direct products of glacial erosion. They consist essentially of unweathered material. Boulders, smaller stones, grit, sand, and the finer-grained rock-meal or flour are all alike fresh; they have not been altered chemically as they would have been had they come from superficial sources. They could not have been derived from above, and they cannot represent the weathered rock-*débris* of preglacial times.

The external configuration assumed by boulder-clay seems likewise to point to the infraglacial origin of the deposit. In relatively narrow mountain-valleys it forms broad terraces or platforms—now trenched and furrowed by streams and rivers. In broad low-land tracts, as in Tweeddale and Nithsdale, it is ar-

ranged in parallel banks, mounds, and ridges, the longer axes of which coincide with the trend of glaciation. Over wide plains, on the other hand, it rises and falls in long, gentle swellings. This varying configuration is undoubtedly original—it is not the result of subsequent subaërial erosion. In mountain-valleys the ice-flow, subject to no deflection, must have proceeded continuously in one direction, and its ground-moraine, we may suppose, would thus tend to accrete more or less regularly. In the broader lowland tracts, however, as in the lower reaches of Nithsdale, Teviotdale, and Tweeddale, the same uniformity of conditions did not exist. Each of these broad depressions was occupied by *mers de glace*, formed by the confluence of ice-flows streaming out from various ice-sheds. Under such conditions the movement of the united currents could not be so equable, and in consequence of variations in the pressure of the ice, and in the lines of most rapid motion, the ground-moraine would tend to heap up in banks or ridges, the longer axes of which would necessarily coincide with the direction of ice-flow.[1]

[1] The "drumlins" and "drums" of Ireland and Scotland appear to be represented in Sweden by certain banks of boulder-clay, which are described by De Geer as a novel kind of radical moraines. He recognises their strong resemblance to the drumlins of New England (*Geol. Fören. Forh.*, 1895, p. 212). Drumlins occur in the Island of Rügen, but they would seem to be rare in North Germany. Recently Dr. K. Keilhack has observed them in Neumark (*Jahrb.*, *d. konigl. preuss. geol. Landesanstalt für* 1893, 1895, p. 190). They have been recognised also in the low grounds of Switzerland by Dr. Früh (*Jahresbericht d. St. Gallischen Naturwissensch. Ges.*, 1894–95). It is probable, however, that the lenticular mounds and banks of till known under the name of drumlins have not all been formed in the same way. Thus the short lenticular

Once more, over the peripheral areas of the inland ice, as in the great plains of Germany, the influence exerted by the confluence of ice-flows just referred to would no longer be felt, at least to the same extent. When the ice had fairly escaped from uplands and hilly ground all minor movements would merge in one continuous broad outflow, the ground-moraine, as a result, being spread out more or less uniformly.

Looked at broadly, Northern Europe displays a central region of glacial erosion and a peripheral area of glacial accumulation. In the former, as in the Scandinavian peninsula, Finland, and the more elevated portions of the British Islands, bare rock is conspicuous over wide districts, while glacial accumulations, confined for the most part to hollows and depressions, attain as a rule no great thickness. Outside of such areas of special erosion, on the other hand, as in the low grounds of England and the plains of Northern Europe, naked rock appears only at intervals, while morainic materials and fluvio-glacial deposits reach their greatest development.

Under the ice-sheet rock-grinding and rock-shattering were carried on side by side. No doubt the boulder-clays frequently rest upon a smoothed and

drumlins of South Galloway appear to owe their origin to glacial erosion. They are the relics of the sheet of boulder-clay which accumulated under the last general *mer de glace* that overwhelmed Scotland. At a later stage the Southern Uplands supported local ice-sheets and large glaciers which, flowing out upon the adjacent low grounds, ploughed into and greatly denuded the old boulder-clay. The drumlins of this region are, in short, simply *roches moutonnées*, composed sometimes entirely of boulder-clay, at other times partly of boulder-clay and partly of solid rock.

striated surface, but just as frequently the ground-rock is shattered, crushed, and jumbled, and the *débris* mixed up with the overlying till. Such phenomena are not confined to any particular area. Examples of finely smoothed and of jumbled rock-surfaces may often be seen in one and the same quarry or other opening. The latter, however, are best developed in places where the ground-rock tended to yield most readily to the pressure of ice. Massive crystalline rocks are perhaps oftener smoothed than shattered below till; but again and again their jointed structure has led to their ready disruption, boulder-clay has been squeezed into their crevices, and numerous blocks, some of large size, have been torn out and enclosed in the till. The result of this infraglacial disruption, however, is better seen in the case of bedded rocks, especially when the dip of the strata has happened to coincide with the direction of ice-flow. In such cases the boulder-clay has often been forced in between the bedding-planes, and broad ledges and reefs of rock have been wedged up and forced out of place. Not only so, but in the case of chalk and certain Tertiary formations, the pressure of the ice-sheet has not infrequently squeezed the rocks into folds and flexures of such a character that the disturbance and contortion have sometimes been attributed to subterranean action. Superficial curving, flexing, and displacement of the kind referred to are met with both in high and low-lying regions; but as the more yielding strata are best developed within

the latter, it is there that we meet with the most striking evidence of infraglacial disruption and quarrying.

From the various facts above referred to we are justified in concluding that glacier-ice is a most effective agent of erosion. It not only abrades, rubs, smooths, and polishes, but crushes, folds, disrupts, and displaces rock-masses, the amount of disturbance being in proportion to the resisting power of the rocks and the pressure exerted by the ice. Other things being equal, more crushing and displacement will be effected under a massive ice-sheet than under a small valley-glacier. It is obvious, therefore, that during the prolonged existence of an ice-sheet, transport and accumulation must result in very considerable modifications of the surface. The central area of dispersion becomes gradually lowered by the abstraction of rock-*débris* which is carried forward and accumulated over the peripheral area occupied by the *mer de glace*. Hence it is that in the former region ground-moraines are seldom very thick, and usually consist of local materials. As they are followed outwards, however, they gradually attain a greater depth, and are more widely spread, the local materials becoming more and more mixed with far-travelled detritus, until eventually the latter begins to predominate. The depth attained by the ground-moraines in the plains of Europe is often great, individual sheets of boulder-clay often exceeding one hundred feet in thickness.

Such boulder-clays, however, are not the only evidence of glacial erosion. With them are frequently associated beds of gravel and sand and laminated clay, consisting exclusively of erratic materials. These are admittedly the products of infraglacial water-action; the materials have been derived principally, if not exclusively, from the washing and sifting of infra- and intra-glacial detritus. Extensive beds of such aqueous accumulations underlie the ground-moraines in some places, and in other places separate one mass of ground-moraine from another. Great mounds, banks, and sheets of the same character, which obviously are similar in origin to the fluvio-glacial detritus of the Alpine *Vorländer*, fringe the margins of the ground-moraines, and sweep over wide areas in North Germany and Russia. All these, therefore, must be taken account of if we would form an adequate conception of the amount of erosion effected by the *mers de glace* of the Ice Age.

The diluvial deposits of North Germany necessarily vary in thickness. Sometimes they are only a few feet, at other times they exceed 200 yards. Dr. Wahnschaffe has collected the results of numerous borings made in those regions, from which we learn that in East Prussia they range in thickness from 20 feet up to 490 feet, in West Prussia from 20 feet to 360 feet, in Posen from 35 feet to 240 feet, in Brandenburg from 30 feet to 670 feet, in Mecklenburg from 6 feet to 430 feet; in the province of Saxony a depth of 400 feet has been noted. Mr. Amund Hel-

land, after conferring with geologists to whom the diluvial accumulations of the great plains are familiar, comes to the conclusion that the deposits probably attain an average thickness of 150 feet. The materials being partly of local and partly of foreign origin, he deducts the former (estimated at 50 feet), and thus obtains a thickness of 100 feet for the detritus derived from Sweden and Finland, and spread over the low grounds of North Germany, etc. According to this geologist, the glaciated areas of Sweden and Finland, which supplied the detritus, are some 800,000 square kilometres in extent (497,120 square miles), while the area in Russia and North Germany over which Swedish and Finnish erratic materials are spread is estimated at 2,040,000 square kilometres (1,267,656 square miles). Were those materials therefore transferred to the lands from which they have been derived, they would raise the general surface by 255 feet. This estimate, it need hardly be said, is a mere rough approximation, and is probably excessive. But even if it be supposed that Helland has exaggerated both the amount of foreign erratic materials and the extent of the area over which it is distributed, we shall still be compelled to admit that the surface of Scandinavia must have been greatly modified by glacial erosion. If we deduct two-thirds from Helland's result we have still left sufficient material to raise the general surface of Finland and Sweden by 85 feet.

In the following chapter reference is made to the

löss as being primarily a flood-loam of glacial times. Much of that occurring in the river-valleys of Central Europe has, no doubt, been derived from the Alpine lands; but the vast accumulations of löss in Southern and South-eastern Russia doubtless owe their origin chiefly to the flood-waters escaping from the margins of the old "inland ice." All these deposits, as we shall see, have been more or less rearranged and modified by subaërial action, but the materials themselves would seem to have resulted, in largest measure at least, from the washing and weathering of glacial accumulations. In short, they are additional evidence of the effective erosive action of flowing ice.

The researches of geologists in North America are on all fours with those carried on in Europe. They tell precisely the same tale. The American boulder-clays, fluvio-glacial gravels, and löss present us with similar phenomena. As in Europe so in North America, broken and ruptured rocks are of common occurrence under the overlying ground-moraines. The ice-sheet, as Dana remarks, "carried *débris* for the most part, not from the slopes and summits of emerged ridges, but from those underneath it. . . . It obtained its load by abrading, ploughing, crushing, and tearing from those underlying slopes and summits. . . . The ice-mass was a coarse tool; but through the facility with which it broke and adapted itself to uneven surfaces, it was well fitted for all kinds of shoving, tearing, and abrading work. Moreover it was a tool urged on by enormous pressure.

A thickness of 1000 feet corresponds to at least 50,000 pounds to the square foot. The ice that was forced into the openings and crevices in the rocks had thereby enormous power in breaking down ledges, prizing off boulders, and in abrading and corroding."

3. *Modifications of the surface produced by glacial action.* Having now learned that glacier-ice is a most effective eroding agent, we have next to consider the modifications of the land-surface brought about by glacial action. Looked at broadly, as we have seen, each glaciated region shows a central area of erosion and a peripheral area of accumulation. Not that erosion and accumulation are confined in this way each to a separate tract, but simply that in the central area erosion is in excess of accumulation, while in the surrounding region the reverse is the case. It will conduce to clearness, therefore, if we consider first the characteristic features which are the direct result of glacial erosion. Thereafter we shall glance at the aspect presented by a land more or less covered with glacial and fluvio-glacial detritus.

Unquestionably the most notable features of a well glaciated country is its rounded and flowing configuration, a configuration which is always most striking when viewed in the direction of glaciation. Tors, peaks, buttresses, and ridges have been smoothed down, escarpments bevelled off, and asperities in general softened. This is the direct result of glacial abrasion, but accumulation also has helped in the production of a flowing contour, for many of the

dimples and smooth depressions upon hill-tops and hill-slopes are more or less due to glacial deposition. While projecting rock-masses have been abraded and removed, irregular hollows, gullies, ravines, and other rough depressions have often been partially or completely obliterated by the deposition in them of morainic materials, abrasion and accumulation together having thus resulted in the production of a more or less undulating surface. In the phenomena of "crag and tail" we see another effect of the same twofold action. Isolated stacks and bastions of rock, which faced the direction of ice-flow, have been rounded and bevelled-off, and frequently a hollow dug out in front, while morainic *débris* has been heaped up behind to form the so-called "tail" of the hill. There are endless modifications of this structure. Thus in many hilly tracts which have been completely overwhelmed by an ice-flow we may often trace series of parallel ridges and intervening hollows of various width, height, and depth, which obviously extend in the direction of former glaciation. These are the result partly of erosion and partly of accumulation. The hollows show where the rock has most readily yielded to glacial erosion, while the ridges consist of irregular-shaped masses and ledges of more durable rocks, and of morainic material which has gathered in their rear. Into these and other details of glacial action, however, it is not necessary to go. For our purpose it is enough to recognise the general fact that glaciation tends to obscure and obliterate the

features which result from the action of the ordinary agents of erosion and denudation. Hence all well-glaciated areas show a somewhat monotonous outline —round-backed rocks, smoothed and undulating hill-slopes and hill-tops,—in a word, undulating contours are everywhere conspicuous.

The effect produced by glacial action is perhaps most strikingly displayed in regions the more elevated portions of which have risen above the surface of the ice, and so escaped abrasion. In the great valleys of the Alps, for example, how strongly contrasted are the glaciated and non-glaciated areas! In the Upper Engadine the valley slopes up to a height of 2000 feet or thereabout are conspicuously abraded, while above that level all is harsh and rugged. It is the same in our own islands, as, for example, in the Outer Hebrides, where the whole area is smoothed and rounded up to a height of 1500 or 1600 feet, above which level the rocks present quite a different aspect.

But glacier-ice does not only abrade and bevel-off prominent rock-ledges, peaks, tors, bastions, and buttresses, it also excavates hollows, which may vary in extent from a few feet or yards in depth and width to great depressions measuring many fathoms deep and not a few miles in extent. Here, however, we come upon the vexed question of the origin of rock-basins, the consideration of which may be conveniently deferred for the present.

The transfer of detritus from the area of dominant glacial erosion, and its distribution over the peripheral

area of dominant accumulation, has very considerably modified the aspect of the land. Could we remove all glacial deposits from our own broad lowland valleys, it is certain that the sea would in many places penetrate far inland. On the continent the Baltic would overflow wide tracts in the plains of Northern Germany, for the bottom of the deposits of that region descends frequently below the level of the sea. And similar changes would be brought about were the glacial accumulations of North America to disappear —the sea would encroach upon the land. Very considerable modifications were likewise effected in the drainage-systems of extensive regions. In Europe and North America alike, the irregular deposition and distribution of glacial and fluvio-glacial accumulations have often led to remarkable changes in the directions followed by the streams and rivers, which reappeared as the great *mers de glace* melted away. Throughout the peripheral areas of dominant deposition preglacial courses and channels were largely filled up with detritus, and not infrequently had become in this way obliterated, so that the streams and rivers of post-glacial times were often deflected and compelled to erode new channels.

It is not with such changes, however, that we are at present concerned, but rather with the various forms assumed by glacial accumulations. Ground-moraines, as we have already seen, present certain typical configurations. And the same is true of lateral and terminal moraines, and of fluvio-glacial de-

posits. In areas of dominant glacial accumulation, as in Schleswig-Holstein and North Germany, the ground-moraines often occupy the surface over extensive regions, and form wide plains with a softly undulating surface. The ground rises and falls gently in long, broad swellings and depressions, which do not seem to follow any particular direction. In other regions, as in the Lothians and elsewhere in our own lowlands, the undulations of the boulder-clay not infrequently show a rudely parallel arrangement. Ever and anon, however, all traces of definite orientation disappear, and the ground then simply rises and falls irregularly as in the plains of North Germany. But in some of the broader dales of Scotland the configuration of the boulder-clay becomes strongly defined, the accumulation being arranged in a well marked series of long parallel banks known as "drums" or "sowbacks." Elsewhere, again, as in Galloway and in many parts of Ireland, the ground-moraines often assume the form of short or more or less abrupt lenticular hills, or "drumlins," as they are termed.

Another set of characteristic glacial land-forms are the eskers, or osar. These are somewhat abrupt banks and ridges of gravel and sand, which are believed to have been formed in tunnels underneath the great *mers de glace*. They are well seen in certain tracts of our own islands, but reach their greatest development in Sweden, where they traverse the land as great embankments, rising to a height of 50 or 100 feet above the general level, and following a sinuous

or river-like course for distances of sometimes 150 miles or more.

Other hillocks and hills of glacial origin are lateral and terminal moraines. The former are practically confined to mountain-valleys, while the latter are met with, not only in mountain-valleys, but in lowlands often far removed from any elevated region. In mountain-valleys such moraines consist chiefly of angular rock-*débris*, but in low grounds opposite the mouths of mountain-valleys they are usually composed more largely of ground-moraine, together with gravel and sand and a certain admixture of angular *débris* and blocks, sometimes the one and sometimes the other kind of material predominating. In Europe, the most remarkable terminal moraines are those which denote the limits reached by the glaciers and ice-sheets of the Glacial Period. They are strongly developed in the *Vorländer* of the Alps, in Southern Scandinavia, Schleswig-Holstein, North Germany, and Finland; and on a smaller scale they abound in our own islands. Looked at broadly, such moraines occur as more or less abrupt mounds and crescent-like or undulating ridges. Opposite the mouths of important mountain-valleys they are often disposed in concentric series, one or more dominant lines of banks and ridges with many subordinate hummocks, heaps, and irregular low mounds lying behind and between them. Not infrequently they present a most tumultuous appearance—cones, mounds, banks, and ridges confusedly heaped together, and thus enclosing

multitudinous hollows and depressions of all shapes and sizes, many of which contain lakes or pools, while others are occupied by bogs or simply clothed with grass and herbage. The hillocks and ridges vary much in height and size, among the most conspicuous being those of Piedmont and Lombardy, where they occasionally attain the exceptional elevation of more than a thousand feet above the adjacent low grounds. More usually in the Alpine *Vorländer* they do not exceed two or three hundred feet. The terminal moraines of the great Baltic Glacier in Finland, North Germany, Denmark, and Southern Sweden present much the same appearance as those of the Alpine *Vorländer*. The most conspicuous are those which mark the extreme limits reached by that great ice-stream. These rise more or less abruptly above the level of the broad plains of gravel, sand, and boulder-clay which sweep outwards from their base into the low ground of North Germany and Poland. The land lying between those external ridges and the shores of the Baltic forms a typical *paysage morainique*—wide plains traversed now and again by winding irregular ridges of gravel and sand, and more or less abundantly sprinkled with mounds and banks of similar materials. Here and there these hillocks crowd more closely together, giving rise to a tumultuously undulating surface; while in other places they are drawn out in curving lines and belts, or bands. Throughout the whole area shallow lakes and lakelets, bogs, and morasses are abundantly developed. The surface of the

flat lands lying within this great morainic tract is usually formed superficially of fluvio-glacial deposits, and the same is the case generally with the low grounds immediately outside of the *paysage morainique.*

To sum up the general results of glacial action, we may say that this action is entirely mechanical. Under the influence of ordinary weathering each particular kind of rock tends to assume a more or less characteristic outline. With glaciation, however, this is not the case. All rocks subjected to glacial action become abraded after one and the same fashion. The tendency of that action is to reduce asperities, to smooth and flatten the surface. But glacial action has usually been arrested long before its work has been completed. It is only here and there that projecting rocks have been ground away and reduced to a plain surface. In most cases they are simply rounded off, and so rocky hill-slopes tend to assume mammiform outlines. Some rocks are, of course, more readily reduced than others; but whether the rocks be hard or soft, they all acquire the same undulating configuration. In regions of dominant glacial erosion the rounded and undulating surface is often in part due to glacial accumulation, the abrupt depressions of the ground being not infrequently filled up and replaced by smoothly outlined hollows.

Where the region of glacial erosion merges into that of glacial deposition, it is often hard to say whether morainic matter or solid rock enters more largely into the formation of the banks and hillocks

that extend outwards from the base of the mountain-area. Eventually, however, we pass into the region of dominant accumulation—the region of ground-moraines and eskers, of terminal moraines, lakes, and fluvio-glacial plains.

CHAPTER XII

LAND-FORMS MODIFIED BY ÆOLIAN ACTION

INSOLATION AND DEFLATION IN THE SAHARA—FORMS ASSUMED BY GRANITOID ROCKS AND HORIZONTAL AND INCLINED STRATA—REDUCTION OF LAND-SURFACE TO A PLAIN—FORMATION OF BASINS—DUNES OF THE DESERT—SAND-HILLS OF OTHER REGIONS—TRANSPORT AND ACCUMULATION OF DUST—LOESS, A DUST DEPOSIT—LAKES AND MARSHES OF THE STEPPES.

AT the outset of our inquiry into the origin of surface features, we briefly considered the general nature of the work done by the principal epigene agents. We saw that these agents are often so closely associated in their operations that their individual share in the final result can hardly be determined. In our country, for example, erosion is effected by the combined action of the atmosphere, of frost, and of rain and running water. There are many regions, however, in which one or other of these agents is by far the more conspicuous worker. Thus, at lofty elevations in temperate regions, and throughout the higher latitudes, the most potent causes of rock-disintegration and removal are frost, snow, and ice. In warm-temperate, subtropical, and

tropical lands, on the other hand, it is usually the chemical and mechanical action of the rain and running water which impresses the observer, while in rainless and desiccated regions insolation and deflation play the most important *rôle*. It is in the latter, therefore, that the erosive action of wind is best displayed. Not that this action is confined to such areas, for it may be observed almost everywhere, and more particularly in mountain-regions. Outside of deserts, however, the wind acts chiefly as a transporter of rock-material. In all latitudes incoherent deposits of sand, exposed and dried, come under its power, and tend to be piled up in heaps and ridges or spread out in sheets. In this way certain more or less prominent land-features owe their origin directly to wind; and as we have devoted some space to the consideration of the action of ice as a special agent of erosion and accumulation, we shall now take a rapid glance at the more notable surface-features that result from the destructive and reproductive action of the atmosphere.

In desiccated regions rock-disintegration and the transport and accumulation of superficial materials are mainly the work of insolation and deflation—rain and running water necessarily play a very subordinate part. This is certainly the case in the Sahara—the most extensive tract of desert in the Old World. This vast region stretches across Africa from the Atlantic coast to the valley of the Nile, and from the northern borders of the Soudan to the Atlas Mount-

ains and the Mediterranean, an area equal in size to two-thirds of Europe. The surface of the Sahara is sufficiently diversified, and is not, as popularly supposed, entirely covered with blowing sand. Dunes, no doubt, spread over enormous territories, but wide tracts and broad basins of loam and clay, with saline lakes and marshes, likewise present themselves, whilst elsewhere rocky and stony plateaux, and even lofty mountains, occupy extensive areas. Ever and anon, moreover, verdant oases appear, and these are so numerous that they must altogether form no inconsiderable portion of the whole Sahara. The entire area might be described as an old plateau of accumulation, built up, as it appears to be for the most part, of horizontally or gently inclined strata. Probably its mean altitude is not less than 2000 feet, only a small portion lying to the south of Algeria being below the level of the Mediterranean. The rocky areas of the region are broken up into a succession of narrower and broader terraces or plateaux—now in many places traversed by dry, winding gullies, ravines, valleys, and other abandoned watercourses, or largely replaced by groups of bare pyramidal hills, buttes, mesas, and irregular rock-masses. Over wide areas blowing sands are absent, while elsewhere they are heaped up and spread out to such an extent that the rocky framework of the country becomes entirely concealed.

Wind erosion is naturally best studied in the bare portions of the desert. Under the influence of insolation the rocks crumble down, and the disintegrated

material is swept onward by the wind. Hard, compact stones acquire a polish like that given by a lapidary's wheel, while rocks of unequal consistency yield irregularly, the softer portions being removed and the harder parts left standing in relief. Where the surface of the land is very uneven the air-currents streaming between opposing heights have ground out deep hollows and gullies. In like manner curious niches, cirques, and amphitheatres have been excavated in the walls of the dry wâdies. Everywhere, indeed, the rocks are abraded, fretted, honeycombed, and undermined. Undermining is, in truth, one of the most notable stages in the general reduction of the surface. The bulk of the sand driven forward by the wind rises only a few feet above the surface, hence cliffs and stacks wear away rapidly below until the overhanging mass collapses and topples down, whereupon the same action is repeated upon the fallen *débris*. Hence isolated rock-masses often take peculiar mushroom-shapes.

Among the most fantastic forms assumed under the action of the wind are those met with among granites and granitoid rocks. Often rising boldly above the general level, they show no trace of talus or *débris*, but are swept bare to the base, and to the fanciful Arab they often simulate the appearance of elephants, apes, camels, panthers, and the like. In Europe granite hills and mountains frequently show rounded summits, and are usually well mantled with talus. In the desert, on the other hand, they are

much more rugged and abrupt, their precipitous flanks bare of *débris*, and their serrated crests and peaks recalling, according to Walther, the bold and abrupt dolomite mountains of South Tyrol. The horizontally arranged strata of the desert assume very

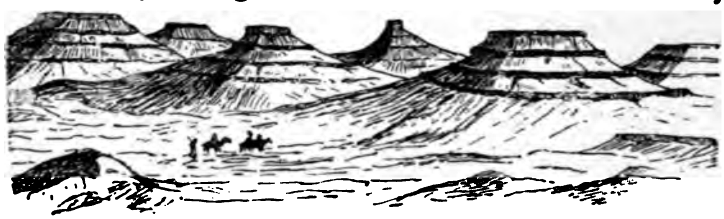

FIG. 79. WIND EROSION: TABLE MOUNTAINS, ETC., OF THE SAHARA (Mission de Chadamès).

different forms, and have been carved into tabular, conical, and pyramidal hills, with a general resemblance to the buttes, mesas, and pyramids of the Colorado region. (Fig. 79.) When the strata are

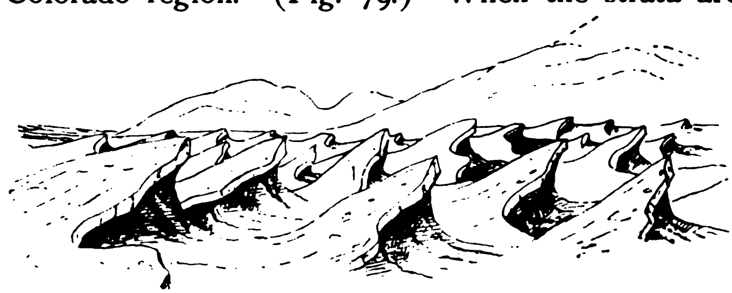

FIG. 80. WIND EROSION: HARDER BEDS AMONGST INCLINED CRETACEOUS STRATA. LIBYAN DESERT. (J. Walther.)

inclined the outcrops of the harder beds project, and we have in like manner a reproduction of the escarpments and dip-slopes which the same geological structure gives rise to in well watered lands. (Fig. 80.)

The projecting ledges and escarpments, however, are always honeycombed and dressed in a different way, betokening everywhere the characteristic action of the wind.

The final result of wind erosion is the reduction of inequalities and the production of a plain-like surface.

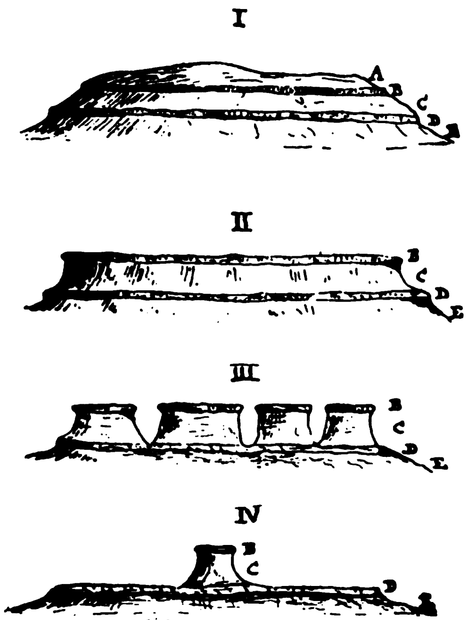

FIG. 81. WIND EROSION: STAGES IN THE EROSION AND REDUCTION OF A TABLE-MOUNTAIN. (J. Walther.)

In the Eastern Sahara wide areas of rocky land have been thus levelled. (Fig. 81.) Such areas are usually more or less abundantly besprinkled and paved with angular stones, usually dark brown or black, and so highly polished that they glance and glitter in the sun.

It is obvious that such stones are derivative; they are the relics of massive beds of sandstone, through which they were formerly distributed, and which have since been gradually disintegrated and removed. In some places, indeed, massive inclusions of the kind (manganese concretions), of all shapes and sizes, project from the surface of the sandstone in which they are still partly embedded. On the lee side of such concretions the sandstone has been sheltered from the attack of the wind, while it has been planed away in

FIG. 82. MANGANESE CONCRETIONS WEATHERED OUT OF SANDSTONE; ARABAH MOUNTAINS, SINAI PENINSULA. (J. Walther.)

front. No stone withstands the action of the wind so well as the hard flints, jaspers, and silicious concretions, which are so commonly met with in the sedimentary strata of the Libyan desert. When the latter have become disintegrated and gradually removed by the wind, the hard nodules and concretions remain, and thus the broad plains are covered over with sheets of "gravel" and shingle. The Sserīr, according to Walther, are nothing more than rocky lands levelled by wind-erosion; the more yielding materials have

been swept away, while the hard inclusions left behind are now concentrated at the surface.

Another result of deflation may be referred to. Now and again in wind-swept plains and plateaux the rocks, according to their nature, are variously affected. Some are disintegrated and rotted more readily than others. These, therefore, tend to be more rapidly reduced below the general level, and shallow basins are thus formed which are sometimes occupied by water for shorter or longer intervals. Such is probably the origin of the Caldeirãos of Bahia, where the general configuration of the surface has some resemblance to that of an ice-worn region—gently rolling ground, namely, showing innumerable shallow depressions winding amongst multitudinous bare-backed, dome-shaped rocks.

The disintegrated material removed from a rocky desert is eventually spread out and piled up in sheets and heaps of sand, which travel onwards in the direction of the prevalent wind. In the Eastern Sahara bare rocky plateaux prevail, and sand-wastes are usually of inconsiderable extent. In the Western Sahara, on the other hand, the whole area is more or less smothered in sand. There vast stretches of dunes move with the trade-winds. Advancing to the south-west, they reach the banks of the Niger and the Senegal, and are here and there forcing these rivers southward. Again, passing to the west, they touch the Atlantic coast between Cape Bojador and Cape Blanco, and stream out to sea so as to form

a belt of sand-banks extending several miles from the shore. For long ages, therefore, a great current of sand has been constantly flowing out of the desert.

The dunes of a desert appear to move more readily than those of maritime regions. Possibly this may be due to the better rolled character of the constituent grains, to the drier condition of the sand, to the want of any binding materials, and the absence of a fixed nucleus, such as is so commonly acquired for the formation of coastal dunes. In the central portions of a desert they are generally arranged in series of long parallel undulations, that extend in a direction at right angles to that of the prevalent wind. Elsewhere they may be more irregular in their grouping and arrangement, individual sand hills not infrequently assuming a crescentic or sickle-like shape. They vary much in height, not often exceeding 250 feet, although occasionally reaching 500 or even 600 feet.

It need hardly be said that dunes are not restricted to desert regions. Wherever incoherent deposits are dried and exposed to the air, they are liable to drift with the wind. Hence blowing sands are well developed upon certain sea-coasts and lake shores, and in the broad, flat valleys of many large rivers. If the surface over which sand is blown be level and free from obstructions, the sand does not necessarily accumulate in heaps and banks, but is often spread out in successive horizontal layers, forming a sand-plain. But wherever obstructions intervene, such as

prominent rocks, trees, bushes, or what not, these give rise to inequalities in the distribution of the sand. A steep talus of grains gathers in the sheltered lee, while a more gently sloping bank gradually rises on the windward side of the obstruction, until this is

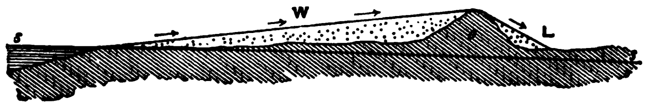

FIG. 83. FORMATION OF SAND-DUNES.

o, obstacle intercepting sand; *w*, windward side; *l*, lee side; *s s*, sea-level.

eventually overtopped and buried. (See Fig. 83.) In this way a dune is formed, and continues to increase until it reaches its maximum height, determined by the strength of the wind and the supply of the materials, and probably in some measure also by the

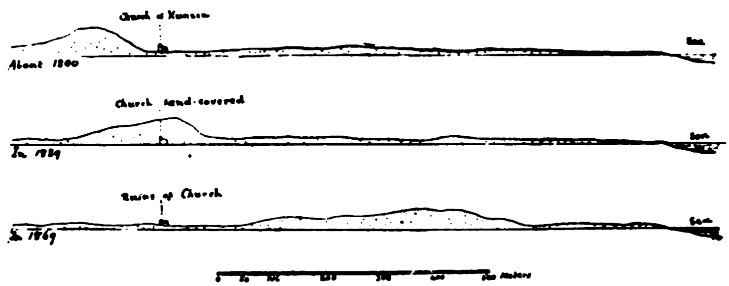

FIG. 84. ADVANCE OF SAND-DUNES,

Illustrated by the burial of a church, and its subsequent reappearance, in the neighbourhood of the Kurisches Haff. (G. Berendt.)

size of the sand-grains. As the sand continually travels up the gentler windward slope, and comes to rest on the steeper leeward slope, it follows that a dune itself must constantly, if slowly, move forwards. Thus in time the nucleus that gave origin

to such a sand-hill may become again exposed. (See Fig. 84, p. 259.)

Coastal sand-hills, like those of inland regions, are frequently arranged in successive parallel ridges or undulations. These, however, are often interrupted by transverse hollows, and the dunes frequently run into one another irregularly. In other places little or no parallel arrangement can be traced, the hills and hummocks showing a tumultuous and tumbled surface of winding and straggling ridges, of isolated banks and knolls, and confused groups of mounds and hillocks, the hollows amongst which form a perfect labyrinth. Should grasses or other vegetation clothe the dunes, these become fixed, but in the absence of any plant-growth the surface of the sand-hills is kept in constant motion by the wind.

In the hollows amongst sand-dunes marshes, pools, and lakes now and again appear. In some parts of the Sahara, for example, long straggling basins of groundwater extend between the sand-ridges. Again, the advance of sand-dunes from a coast has often obstructed the natural drainage, and formed swamps and lakes of larger or smaller extent. The lagoons, which in many places are separated from the sea, have frequently been cut off from the outside ocean by the combined action of the waves and the wind in raising up sand-banks and -dunes.

In desert regions the bulk of the sand driven forward by the wind rises to no great height above the surface; its abrading and scouring action is largely

confined to the basal portions of the rocks against which it is borne. But the finer-grained matter—the powdery dust—is often swept upwards to great heights, and may be transported for hundreds or even thousands of miles from the place of its origin. As might have been expected, however, it is over the region immediately surrounding a desiccated area that the dust chiefly falls. In time such regions become more or less thickly mantled with this dust, which usually yields a fertile soil. After long ages of accumulation the whole surface of the dust-covered tracts becomes greatly modified. Inequalities are smoothed over, and everywhere softly flowing features are produced. As no hard-and-fast line separates an area of wind-erosion from one of dust-accumulation, sand and dust become commingled along the borders of the two regions, or there is a gradual transition from the one kind of material to the other. The fertility of the Nile Valley is rightly attributed to the fine silt and loam of the annual floods, but desert-dust has also added its share to the soil of Egypt. Similarly it is believed that dust has played an important part in the formation of the fine porous soils of many other lands. According to Baron Richthofen, the vast löss accumulations of China are true dust-deposits. Löss is a fine-grained, homogeneous calcareous and sandy loam, penetrated vertically by numerous root-like pores and tubes, which have the same effect on the deposits as joints in rocks—they allow the löss to cleave in a vertical direction. When

it is intersected, therefore, by streams and rivers it forms bold bluffs and cliffs. It usually contains land-shells, and now and again the bones of land animals. Fresh-water shells rarely occur, while marine organisms are wholly wanting. In Northern China this remarkable accumulation covers vast areas, and attains in places a thickness of 1500 feet or even of 2000 feet. The regions occupied by it have the aspect of extensive plains, which look as if they might be traversed with ease in any direction. They are abundantly intersected, however, by deep valleys and precipitous rock-like gullies and ravines, in the vertical walls of which the natives have excavated their dwelling-places. Richthofen believes that this great deposit has been gradually accumulated by the winds flowing outwards from the desiccated regions of Central Asia. Vast quantities of fine sand and dust are there swept up during storms and scattered far and wide, and in this manner adjoining territories, such as the grassy steppes, are ever and anon receiving increments to their soil. The finely sifted material thus obtained is highly fertile and favours the growth of the grasses, so that every fresh deposit of dust tends to become fixed, and the steppe-formation continues to increase in thickness. It is this continued growth of vegetation, keeping pace, as it were, with the periodical accumulation of soil, which is supposed to produce the porous capillary structure referred to above as the cause of the vertical cleavage of the löss.

Löss occurs in many other countries, but it nowhere attains so vast a development as in China. In Europe we meet with it in the valley of the Rhine and in the low grounds traversed by the Danube, where, although it forms no enormous plains like those of Northern China, it nevertheless mantles the ground so as in some measure to conceal the older features of the land. The extensive sheets of black earth which cover the surface of the great plains of Southern Russia are also a variety of löss. The origin of the European deposits has been much discussed by geologists, but it seems to be now the general opinion that the materials of the löss were, in the first place, introduced into the low grounds chiefly by the flooded rivers and inundations of the Ice Age. Muddy water escaping from the glaciers of the Alps and other mountains, and from the terminal front of the great "inland ice" of Northern Europe, doubtless drowned wide areas, while torrents derived from the melting snows of extraglacial tracts must likewise have swept down large quantities of fine-grained sediment. Thus, long after the periodical inundations of glacial times had diminished in extent and finally ceased, the lower reaches of the great valleys and the broad plains, formerly subject to floods, must have been more or less sheeted with sandy loams. We know now that Tundra- and Steppe-conditions have succeeded in Central Europe. Already towards the close of glacial times a well marked Tundra-fauna had spread south to the Alps and west into France

and England. At that period the climatic conditions were probably such as are now experienced in Northern Siberia. Eventually, however, these conditions gradually gave way,—the Tundra-fauna began to retreat, until by and by it was supplemented by a no less characteristic Steppe-fauna, the range of which seems to have been as extensive as that of the former. The Arctic lemming, Arctic fox, reindeer, musk-ox, and glutton of the Tundras were now replaced by the jerboa, pouched marmot, tailless hare, little hamster rat, and other forms, the common denizens to-day of the Steppes of Eastern Russia and Western Siberia. It is certain, then, that a dry Steppe-climate has prevailed at no distant date, geologically speaking, throughout Central and Western Europe. Thus we may be sure that dust-storms must formerly have been as common in France and Belgium and the regions lying to the east as they are now in Russian and Asiatic Steppes. It was during the prevalence of such climatic conditions, as geologists think, that the wide-spread flood-loams of the Glacial Period were so largely re-assorted and remodified by deflation, and the lössic accumulations assumed their present aspect and distribution.

Mention has been made of the fact that marshes and lakes occur now and again in the hollows amongst sand-dunes. They are met with likewise amongst dust-deposits. Thus pools and large and small sheets of water sometimes dapple the surface or extend over broad areas of the wind-swept Steppes. Such basins,

doubtless, are partly due to the unequal distribution or heaping-up of fine sand and dust. In some cases, however, they seem to have been caused by the unequal removal of superficial materials.

In fine, then, we conclude that wind-erosion is most effective in dry, desert regions. Its influence is, no doubt, world-wide; but as an active agent in levelling the land—in cutting, carving, undermining, and removing rock—wind plays the dominant part in desiccated lands. We note, further, that the forms assumed by rocks subject to wind-erosion are largely determined by geological structure and the nature of the rocks themselves, just as in temperate latitudes feeble structures and relatively soft rocks are the first to yield. Lastly, we recognise that certain wind-blown accumulations have a world-wide distribution, and occur under all conditions of climate. Sand-dunes may be met with wherever incoherent deposits of sufficiently fine grain are exposed to the action of the wind. Dust, on the other hand, is pre-eminently a product of relatively dry regions and of deserts—wherever, indeed, the land is naked or only partially clothed with vegetation, dust is formed, and may be swept up and transported by the wind.

CHAPTER XIII

LAND-FORMS MODIFIED BY THE ACTION OF UNDERGROUND WATER

DISSOLUTION OF ROCKS—UNDERGROUND WATER-ACTION IN CALCAREOUS LANDS—KARST-REGIONS OF CARINTHIA AND ILLYRIA—EFFECTS OF SUPERFICIAL AND SUBTERRANEAN EROSION—TEMPORARY LAKES—CAVES IN LIMESTONE—CAVES IN AND UNDERNEATH LAVA—"CRYSTAL CELLARS"—ROCK-SHELTERS—SEA-CAVES.

IN Chapter VII. it was pointed out that subterranean action had played a most important part in the production of certain surface-features. In particular it was shown that depression of the surface has frequently taken place as a result of that action. We have now to consider another kind of action altogether, which, although by no means so important as that just referred to, nevertheless now and again causes the surface in certain regions to subside. Rocks, as we have seen, are very variously acted upon by water—a few are readily soluble, but the great majority are not. The most important of the soluble rocks are rock salt, gypsum, and limestones of every kind. These are all more or less easily removed by meteoric water. Rock salt is so very soluble that it is seldom

or never found cropping out at the surface; any surface-exposure in temperate lands would rapidly disappear. It is only in dry and rainless tracts, therefore, that rock salt can exist as a superficial accumulation. Gypsum is more readily dissolved than limestone, but both rocks become eaten into at the surface, and, according to circumstances, are more or less rapidly washed away. This process of dissolution, it is needless to add, is not confined to the surface. Meteoric water penetrates the ground, and circulates through the crust to considerable depths. After pursuing a shorter or longer course, it reappears at the surface as springs, the waters of which are more or less abundantly charged with dissolved mineral matter, according to the nature of the rocks through which it has passed. In this way enormous quantities of soluble materials are brought up from below; in short, wholesale chemical erosion goes on underground. It follows that in regions where soluble rocks enter largely into the framework of the land the surface must in time subside slowly or suddenly. The copious outpouring of brine-springs gradually reduces beds and sheets of rock salt, and the overlying strata sink down and thus produce depression at the surface. And the same result is brought about by the dissolution of gypsum, limestone, and dolomite. Sometimes the surface slowly subsides, but now and again it collapses suddenly, producing earthquakes, accompanied by much fracturing and shifting of the rocks. Thus it is believed that the earthquakes which disturbed

the Visp-Thal in Valais during the summer and autumn of 1855 were the result of the caving-in of the rocks consequent on the dissolution and removal of gypsum, for the springs of that district bring to the surface annually over 200 cubic metres of the mineral in solution. Similarly, it can hardly be doubted that many of the larger and deeper depressions of the surface which appear in regions of calcareous rock are the result of sudden collapse due to the removal of material by underground water.

As rock salt and gypsum do not enter largely into the composition of the crust, they are less important from our point of view than limestones. The latter not only attain in many cases a much greater thickness, but they are far more widely distributed, and extend over much broader areas of the earth's surface. It is in regions of calcareous rocks, therefore, where underground water plays the most prominent *rôle*, and where its action in modifying surface-features is best displayed. In a former chapter reference has been made to the fact that in countries occupied by limestone, the drainage is often largely or even wholly conducted underground. The rocks are so penetrated in all directions by rifts, clefts, and tunnels, that the water which falls at the surface very soon disappears. Concerning the origin of these subterranean spaces there is not much difference of opinion. Geologists recognise that they have been worked out by chemical and mechanical water-erosion. But while some have maintained that the underground water

has licked and worn out a passage for itself chiefly along the normal divisions of the rocks—their joints and bedding-planes—others have held that the main lines of underground drainage have been determined by faults or dislocations. Both views are doubtless true: some caves and underground tunnels appear to have no connection with faults; others, on the contrary, follow these, although many of the channels connected with them have been worked out along joints and bedding-planes.

Underground water usually follows a zigzag and irregular course—now plunging downwards at high angles, or even vertically, through relatively constricted clefts and fissures; now winding through approximately horizontal tunnels, or forming lake-like expansions in broad and lofty halls and chambers; now dividing into more or less numerous torrents and streams, which zigzag downwards to lower and lower levels. In time many changes are effected. Here and there passages are blocked with sediment or by falls from the roof, and become partially or wholly abandoned, the water, dammed back, rising and making its escape by other clefts and hollows. Thus eventually the limestone becomes traversed in all directions by a perfect net-work of intercrossing channels—winding and angulate, low and lofty, broad and narrow—many of which become abandoned by the water as it works its way to lower and lower levels. To what depth from the surface considerable tunnels can be excavated by chemical and mechanical

erosion we cannot tell. It is obvious, however, that a limit must be reached when the pressure of the superincumbent and surrounding rocks becomes so great that no vacant spaces can exist. Water descending from the surface must thus eventually be forced by hydrostatic pressure to rise again and escape at lower levels than its source. Large underground channels, therefore, probably descend to no great depth from the surface, and their size is naturally limited by the structure of the rock in which they are excavated. Where this is much jointed and fissured it is obvious that the span of a cavern cannot be great; the disjointed rocks, losing support, tend to collapse. The widest underground chambers do not exceed 100 yards in width.

In course of time the whole surface of a country is gradually lowered by denudation. This change goes on most rapidly no doubt in regions where the superficial rocks are more or less impermeable. But lands composed chiefly of limestone do not escape—corrosion, especially, proceeds more or less rapidly. Ever and anon, too, the surface sinks slowly or suddenly as the case may be, consequent on the withdrawal of rock-material from below. The peculiar deformations caused by such changes are among the most characteristic features of limestone regions. Typical regions of the kind show no regular river-systems; brooks and rivulets are wanting. Water sinks at once into the ground by pipes and swallow-holes, clefts and fissures. In the lower-lying parts of such lands now

and again rivers suddenly emerge at the surface, and after usually a short course may again disappear below ground. In the rainy season water often rises through the apertures by which the surface is more or less abundantly pierced, and dry valleys and wide basin-shaped depressions become flooded. Of course when the supply fails the water again returns to the depths from which it was discharged.

In the karst-regions of Carinthia and Illyria these phenomena are very well displayed. The funnel-shaped depressions communicating with underground galleries, which with us are termed swallow-holes, are known in Carinthia as *dolinas*. These vary in width and depth from a few yards up to half a mile in width, and from 100 to 200 yards and more in depth. Most of them, however, are small—40 or 50 yards across, and about 30 yards or so in depth. Their bottom is somewhat flat, and often covered with loam or clay. The larger ones are relatively shallower in proportion to their width than the others. Not less characteristic features of the karst-lands are the so-called blind-valleys and dry-valleys. Through the former a river flows to disappear into a tunnel at the closed or blind end. The dry-valleys have no river; the bottom is usually irregular and often pitted with dolinas. Besides these land-forms, geographers recognise another kind of depression, the so-called "kettle-valleys," which are trough-like or dish-shaped basins of variable extent, some of them having an area of several hundred square miles. Not infrequently the smaller

ones run in parallel zones following the direction of the strike of the strata. All these surface-features are for the most part the result of underground erosion. Some of the dolinas may have been eroded by water descending through fissures from the surface; but probably the greater number, and certainly all the larger ones, have been caused by the caving-in of underground tunnels. So, again, the blind-valleys and dry-valleys appear in most cases to form part of the subterranean drainage-system, now exposed by collapse of roof and the general degradation of the surface. The natural bridges or arches which are seen often enough in such regions are simply the relics of old underground tunnels and waterways, the ruins of which often cumber the depressions of the surface. It is hardly worth while adding that the numerous limestone caverns in which geologists have hunted so successfully for remains of primeval man and his associates are merely the abandoned courses of ancient underground streams and rivers. Almost everywhere, indeed, in great limestone-regions one may trace at the surface evidence of the effects produced by subterranean erosion. The trough-shaped basins (kettle-valleys) referred to above seem to owe their origin in the first place to determinate fissures. These are widened by the action of the surface-water as it passes underground, and the depression at the surface increases as the rock becomes undermined, collapse taking place from time to time. If the collapse be recent the bottom of the kettle-valley is

strewn with broken rock-*débris*. Not a few kettle-valleys in limestone-plateaux, however, may have been partially excavated by superficial water-action before the system of underground drainage was established, but by the action of the latter they have since been more or less modified. It may be taken as generally true that most of the depressions or basins, great and small, which are so characteristic of karst-lands, are either largely or wholly due to the corrosive and erosive action of underground water.

Lakes, as we have seen, often appear periodically in these regions. Some are very regular in their coming and going, others only show at intervals after unusually heavy rain or long-continued wet weather. One of the best-known examples is the Lake of Jessero, or Zirknitz, in Carniola, which appears now and then in the broad valley of the Planina. This river, after flowing underground for a long distance, returns to the surface, and shortly afterwards winds through a wide plain encircled by high cliffs of limestone. The plain is pierced by hundreds of dolinas, from which, after excessive or continuous rain, the water wells and rushes until the whole wide area is transformed into a lake. The extent and depth and the duration of this temporary lake vary; and the intervals between its successive appearances are likewise inconstant; sometimes only a year, or two or three years may elapse, but intervals of ten and even of thirty years have been experienced. Not a few depressions in the surface of calcareous tracts may be

rendered impermeable by the accumulation in them of loam and clay, and these may then be occupied by permanent lakes.

The influence of subterranean water is not, of course, confined to regions of soluble rocks. Where-ever water circulates in the crust rocks are attacked, and their constituents become liable to chemical change. In this manner immense quantities of mineral matter are brought up from below, some of it to be thrown down at the surface, where in time it may form massive accumulations. The mechanical action of subterranean water is also recognised almost everywhere, and more particularly in places where the geological structure is weak, where rocks are in a state of unstable equilibrium. But the effect of underground water in bringing about rock-falls and landslips in such regions has already been sufficiently discussed.

Although caverns naturally occur most numerously and attain the largest size in the more readily soluble rocks, they are also met with in many other kinds. They appear, for example, not infrequently in lava. Some of the smaller of these are merely large blisters or bubbles, formed by the segregation of the absorbed water-vapour while the lava was in a semi-fluid condition. The more extensive lava-caves have a different origin. While lava is flowing it necessarily cools rapidly at the surface, and in this way becomes crusted over. If the crust thus formed be of sufficient thickness and strength, it remains steadfast, forming a kind

of tunnel, out of which the still liquid lava issues. Such lava-caves are of common occurrence in Hawaii, Mexico, California, the Canary Islands, Iceland, etc. Some are only a few feet in height and breadth, others may be 20 to 30 feet broad, 6 to 10 feet in height, and many yards in length. In certain volcanic regions lava-caves obtained much larger dimensions, but there is reason to believe that these have been modified by subsequent erosion. One in Hawaii has a width at the entrance of 130 feet, a height of 20 feet, and a length of 260 feet. Another (the Raniaka Cave) is 1200 feet long. Water flowing in cavities under the lava-coulées of Auvergne (as in the neighbourhood of Clermont) has cut out courses in the subjacent granite, and issues at the lower ends of the lava-streams through natural arcades. And many similar examples of subterranean tunnels and caves might be cited from other regions, where the erosion has been effected chiefly by the mechanical action of water upon relatively insoluble rocks.

Mention may also be made of the great cavities which occasionally occur in faults. The spaces between the two walls of a fault or dislocation are usually filled up either with rock-*débris*, or subsequently infiltrated mineral matter, or with both. Now and again, however, the filling-up is only partial, and chambers of some size remain. These are often lined with finely crystallised minerals, and form what are known in Switzerland as "crystal-cellars."

Of caves solely due to erosion it is not necessary to

say much. Shallow caves (rock-shelters) are frequently met with in river-valleys, where one can see that they owe their origin to the under-cutting action of the water. More extensive are the caves often excavated by the sea. These necessarily vary in appearance with the character of the rocks in which they are excavated. The presence of a cave indicates some weak structure—some rock or rock-arrangement which has offered less resistance to the attack of waves and breakers. Vertical dikes of basalt, for example, are often so abundantly jointed, that they are broken up and removed more readily than the rocks they traverse, although the latter may consist of "softer" material, such as sandstone. The highly jointed basalt, notwithstanding its superior hardness, is easily shattered. The mere force of the waves combined with hydraulic pressure in some joints, and the compression and expansion of air in others, suffices to rupture and burst the weak structure, and with each drop of the wave large and small fragments may sometimes be seen falling from the roof and sides of the cave. The cave thus increases in height as the sea works its way inland, until not infrequently it communicates with the surface by a "blow-hole," through which in storms not only spray but spouts of water, and even gravel and larger stones, are ejected. Similar caves are frequently formed in well jointed sandstones and in many other kinds of rock. They are very common, for instance, in Orkney and Shetland, and they are well known also in Cornwall and the

West of Ireland. In time the whole roof of such caves may give way, and the latter then appear as narrow ravine-like or gorge-like inlets. This can happen only when the land-surface does not rise to any great height above the sea. When the rocks above a sea-cave are too strongly built or too thick to permit of a downfall of the roof, the cave may attain very considerable dimensions. But as all rocks are traversed by lines of weakness, a limit must be reached beyond which caves cannot be widened. By and by the rocks will cease to be self-supporting, and collapse must take place.

Caves of marine origin are seldom met with far removed from existing coast-lines. They are naturally confined to the latter, and to those lines of old sea-level known generally as "raised beaches." Their position at the base of old sea-cliffs renders them liable to early obliteration, for they tend to be obscured by, and eventually to be concealed underneath, a talus of *débris*. They are not singular, however, in that respect, for many of the most interesting and important of the limestone caverns of Western Europe have been hidden in the same way, their discovery having been the result either of mere accident or of patient scientific research.

CHAPTER XIV

BASINS

BASINS DUE TO CRUSTAL DEFORMATION—CRATER-LAKES—DISSOLUTION BASINS—LAKES FORMED BY RIVERS—ÆOLIAN BASINS—DRAINAGE DISTURBED BY LANDSLIPS—GLACIAL BASINS OF VARIOUS KINDS, AS IN CORRIES, MOUNTAIN-VALLEYS, LOWLANDS, AND PLATEAUX—ICE-BARRIER BASINS—SUBMARINE BASINS OF GLACIAL ORIGIN.

ALL the varied topographical features of the land owe their origin either to subterranean or to superficial agents, or to both. This is true of elevations and depressions alike. It would seem possible, therefore, to classify hollows according to the mode of their formation. Not a few, however, are of complex origin, having resulted partly from hypogene and partly from epigene action. Indeed, we might group all basins roughly in two divisions, according as they owe their origin more or less directly to crustal deformation and fracture, or to the action of surface-agents. Epigene action, however, is so manifold and diverse—the agents of erosion, of transport, and accumulation act in so many different ways—that a more detailed grouping is desirable. Any classification adopted must be more or less arbitrary and in-

complete, but it will serve our purpose to group basins as follows :—

1. Tectonic basins.
2. Volcanic "
3. Dissolution "
4. Alluvial "
5. Æolian "
6. Rock-fall "
7. Glacial "

1. *Tectonic Basins.* These owe their origin directly to deformation of the earth's crust, whether the result of warping or of fracture, or both. In this class are included many inland seas, and most of the larger lakes of the globe. The Aralo-Caspian depression, with its numerous sheets of water and desiccated basins, the Dead Sea, Issyk-Kul, the lakes of Equatorial Africa, the Great Salt Lake of Utah, and very many others are true tectonic basins. A large number of such basins occur in relatively dry and rainless regions. On the other hand, many are met with in temperate regions. The great fresh-water lakes of North America and Europe (Superior, Huron, Michigan, Ladoga, Onega, etc.) occupy tectonic basins. These lakes, it will be noted, are confined to the glaciated areas of the two continents, and their character as tectonic basins has been modified and obscured by glacial erosion and accumulation. There seems no reason to doubt, however, that the depressions are the result of crustal deformation. Tectonic basins are usually somewhat flat-bottomed or

gently undulating. Occasionally they are traversed by narrow winding hollows, which have been traced for longer or shorter distances. These have frequently the character of river-ravines and valleys, and are suggestive, therefore, of a former land-surface which has become depressed. Similar indications of depression are afforded by the highly indented coast-lines of some of the larger lakes of this class, the long inlets and projecting headlands recalling the appearances presented by the fiord-coasts of Norway and Scotland.

The crustal deformation may consist of simple subsidence—a wide area of relatively flat or gently undulating land sinking below the level of adjacent tracts; or the subsidence may be the effect of dislocation and displacement. Again, basins have come into existence between contiguous high grounds undergoing elevation. Once more, the formation of an anticline across the drainage-area of a lowland region might bring extensive lakes into existence. Similarly it is conceivable that lakes might be formed in mountain-valleys by the swelling up of the crust at the base of the mountains, or by the formation of new flexures in the mountains themselves, having a direction transverse to the valleys. We cannot, however, point to any particular valley-basin formed in this way. Earth-movements of this kind would seem to take place very slowly, so slowly, as a rule, that rivers are able to saw across the obstructions as fast as they rise.

2. *Volcanic Basins.* The lakes of this class form a well marked group, many of them occupying the sites of extinct volcanoes. Not a few, therefore, occur in the cup-shaped depressions of volcanic cones. Others, again, may not be walled round by volcanic ejecta, but occupy explosion-craters—the more or less deep concavities produced by paroxysmal outbursts. No hard-and-fast line, however, can be drawn between these two varieties of crater-lake. Some explosion-craters are encircled by ridges of ejecta, while the cup-shaped depressions of certain volcanic cones are of such a depth that, were the cones themselves to be removed, a considerable concavity would still remain. Amongst well known crater-lakes are the Maars of the Eifel, some of which are 70 feet or less in depth, while others are not much below 200 feet. Of the same character are the crater-lakes of Auvergne, which vary in depth from less than 100 to 350 feet; and the similar lakes of Central Italy, one of which, Lake Bràcciano, is said to be 950 feet deep. In all the great volcanic regions of the globe, indeed, lakes of this character are recognised. Other volcanic lakes have had a different origin. Sometimes lava, at other times fragmental ejecta, or streams of tufaceous mud and *débris* have entered valleys and obstructed the drainage. The Lac d'Aydat of Auvergne, for example, is confined by a barrier of lava, and the same is the case with the large Yellowstone Lake. So, again, the enormous torrents of mud and *débris* which poured down to the low grounds during

the great eruption of Bandaisan in 1888 gave rise to four volcanic barrier-lakes. After volcanoes have erupted for a prolonged time the ground often becomes depressed, and large and small subsidences of the surface are not infrequently the result of the earthquakes that accompany volcanic action.

3. *Dissolution Basins.* In regions of soluble rocks, as we have seen, many inequalities of the surface are brought about by the chemical and mechanical action of underground water. Most frequently the depressions produced by the collapse of subterranean galleries and caves contain no water. Sometimes, however, as Professor Penck has pointed out, warping of the crust has brought the corroded and tunnelled limestone rocks under the influence of the subterranean water-level, so that sink-holes and other superficial depressions have become more or less deeply filled. Again, should tectonic movements carry down a honeycombed calcareous region so that its basal portions sink below the sea-level, the meteoric water descending from the surface will be dammed back in sinks and other hollows. The water-surface of wells in such districts is known to rise and fall with the tide. From various causes, also, the underground outlets of dolinas, etc., become closed with accumulations of insoluble earthy materials, and the bottoms of other depressions are rendered impermeable by similar deposits washed into them by rain- or snow-water. Similar changes have been brought about by glacial action, the outlets for the escape of under-

ground water having been closed by morainic *débris*. For these and other reasons lakes are by no means always wanting in regions of highly honeycombed and tunnelled calcareous rocks.

Soluble rocks deeply covered with strata of more durable character do not escape corrosion, but are gradually removed by underground water, and thus bring about slow subsidence or sudden collapse of the surface, and the shallow basins formed in this way may become filled with water.

4. *Alluvial Basins.* The broad alluvial flats of rivers often show slight depressions caused by irregular accumulation. These during floods may become lakes, and endure for a longer or shorter time. Again, rivers tend to change their courses, and their deserted loops often persist as lakes. In rainless regions the rivers flow with a gradually lessening volume, until eventually they may dry up. It is obvious that the sediment transported by such rivers must gradually raise the level of their lower courses, and in time produce shallow basins. In the dried-up courses themselves pools and "creeks" not infrequently occupy the deeper hollows, and are probably maintained by water coming from underground sources. Once more, in well watered regions rivers now and again form lakes. A main stream, for example, by carrying down large quantities of detritus, tends to raise the surface of its bed above that of its tributaries, in the lower reaches of which lakes thus come into existence. In like manner tributary streams occasionally

throw more detritus into the main valley than the river in the latter can at once dispose of. Partial dams are thus produced, and large valley-lakes form above the obstructions, of which the Silser See and Silvaplana See in Upper Engadine are examples.

5. *Æolian Basins.* Another class of basins owe their origin to the action of the wind. Some are erosion-basins caused by the removal of loose, weathered rock-material. Professor Pumpelly seems to have been the first to recognise basins of this kind, which were observed by him in Mongolia. They have since been encountered in many other regions, as in Bahia, in Central Asia, and elsewhere. Sometimes these basins form temporary lakes, at other times the water remains more or less persistently. Some interesting examples have been described by Mr. G. K. Gilbert as occurring in Arkansas and elsewhere in the Great Plains of North America. Basins of this kind are naturally confined to relatively dry regions—to regions where the rocks and soils are not sufficiently protected by vegetation. Reference may also be made to the temporary or more persistent lakes which owe their origin to the unequal distribution of wind-blown accumulations, some account of which has already been given.

6. *Rock-Fall Basins.* Rock-falls and landslips not infrequently disturb local drainage, and may cause lakes to appear. Many small lakes of this class occur in the Alps and other mountain regions where the geological structures are weak and liable to collapse.

7. *Glacial Basins.* The basins coming under this head are essentially of two kinds. Some are hollows of excavation, others owe their origin to the unequal heaping up of glacial and fluvio-glacial deposits. It is not always possible, however, to distinguish sharply between the two. In many cases excavation and accumulation have alike been concerned in their formation. The glacial origin of both is at once suggested by the fact that they are confined to regions which yield other and independent evidence of former glacial action. We note further that their presence has no immediate or direct connection with the character of the rocks or with the geological structure of the tracts in which they lie. They occur in crystalline, igneous, and schistose rocks, and in sedimentary strata of all kinds and of all degrees of induration—conglomerate, sandstone, greywacke, clay-slate, shale, limestone, gravel, etc. They are not restricted to areas of folded, contorted, and fractured rocks, but appear with all their characteristic features equally well developed in places where the strata are gently undulating and approximately horizontal.

The formerly glaciated areas of the earth's surface are pre-eminently the lake-lands of the world. We have only to look at a series of good maps to see that this is the case. Taking Europe as an example, we find that very few lakes occur in regions over which ice-sheets and glaciers have not at one time extended, the most notable of those lakes being the

volcanic basins of Auvergne, the Eifel, and Central Italy. What non-glaciated region of our continent can show a lake-dappled surface like Finland? Where in extraglacial tracts can we find anything to compare with the *paysage morainique* of North Germany and Russia? Precisely the same phenomena confront us in North America. How abundantly are lakes distributed over all the vast tract formerly occupied by the great inland ice! South of the glacial boundaries they are practically unknown.

We note further that the vertical distribution of the class of lakes now under consideration is not less suggestive of their origin. Cirque-lakes and other high-level lakes are not confined to any one region, they occur in mountain-tracts all the world over, wherever these have formerly nourished glaciers. Low-lying valley-lakes like those of the Alps have, on the other hand, a much more restricted distribution. They abound in the mountains of temperate latitudes, where great valley-glaciers formerly existed, but they are looked for in vain in the mountains of the warmer zones, the lower reaches of whose valleys have never been glaciated. Again, in the northern tracts of Europe and North America glacial basins are not even confined to mountain-valleys, but occur more or less abundantly over the lowlands that sweep out from the mountains. In a word, there is a close connection between glaciation and the development of lake-basins.

Basins of glacial origin naturally vary much in char-

acter, according to their position and the particular mode of their formation. Some, as mentioned above, are rock-basins, others are barrier-basins, and many are partly both. It must be added that not a few lakes met with in glaciated regions are not of glacial origin. This is particularly the case in mountain-valleys, where barrier-basins have often been formed by rock-falls and fluviatile action. Glacial basins may be roughly grouped as follows :—

1. Cirque or Corrie basins.
2. Mountain-valley basins.
3. Lowland and Plateau basins.
4. Ice-barrier basins.
5. Submarine basins.

1. *Cirque* or *Corrie* basins are confined to mountain regions. Frequently they appear as niche-like indentations on mountain-slopes at high elevations above the bottoms of the adjacent valleys. At other times they are set farther back from the brow of a valley, forming cup-shaped depressions in the flanks of the higher crests and ridges. When such is the case the water escaping from them may flow for a longer or shorter distance before it reaches the terminal shoulder of a mountain to plunge downwards to the valley below. In detail, cirques vary in character with the nature of the rocks and their geological structure. Many have a crater-like appearance, some of the wider ones resembling the section of a steep-sided amphitheatre, while the narrower ones show

more abrupt slopes. Although now and again the converging slopes may be relatively smooth and not so steep, yet as a rule they are rugged and precipitous, showing bare, gaunt walls of rock, trenched and furrowed by torrent action and shattered by frost. In regions which have formerly supported glaciers cirques are more or less flat-bottomed, or saucer-shaped, and consequently many are occupied by lakes. It is worthy of note that such corrie-lakes, or tarns, are usually deeper in proportion to their extent than the large valley-lakes of lower levels. Many corrie-lakes rest in true rock-basins; others seem to be wholly dammed by moraines; while yet others are partly rock-basins, partly barrier-basins. Not a few have been drained by the water escaping from them cutting back its channel. Others, again, would seem to be filled up by rock-falls and the detritus and *débris* shot down from the surrounding heights. Many cirques, on the other hand, have never contained lakes, their flat bottoms sloping gently, but continuously, outwards. That cirque-basins have been formerly occupied by glaciers is shown by the presence of moraines and the frequent appearance of *roches moutonnées* and striæ, the direction of which indicates an outflow of ice from the depressions. These marks of glacial action are confined to the bottom of a cirque; the precipitous rock-walls show none.

The question of the origin of cirque-lakes has sometimes been obscured by confounding the origin of the cirques with that of the basins which occupy their

bottoms. While some geologists have attributed both to the action of glacier-ice, by others they are believed to be the result of aqueous erosion. The cirques themselves are doubtless in many cases the work of converging torrents, aided by frost. Very frequently, however, frost, rather than running water, has been the chief eroding agent, as may be seen in Norway, where, in immediate proximity to the *névé*-line, cirques are now being formed. The basin at the bottom of a cirque, however, is the work neither of running water nor of frost alone, but has been ground out by glacier-ice. In the Highlands and the Southern Uplands of Scotland the head-waters of streams and rivers often proceed from cirque-basins, especially in the more elevated districts. Many of the smaller feeders, however, come from cirques which have no basin, and this is particularly the case in the less elevated portions of the mountain regions. The origin of the latter is obvious; we see them being formed at present. Springs, summer torrents, snow-water, and frost—all play their parts. The converging mountain-slopes direct the drainage to one point, the result being the formation of a more or less abrupt funnel-shaped depression resembling the section of an inverted hollow cone. The formation of a basin at the apex of this inverted cone by aqueous action is impossible. The torrent escaping from the cirque simply digs its channel deeper, cuts its way back, and by its undermining action tends to increase the slope of the surrounding walls. Add to this the action of frost in splitting up the rocks and

detaching larger and smaller masses, and one can readily understand how a cirque must increase in extent. Cirques of this character occur under all conditions of climate and in every mountain region of suitable structure, in temperate, subtropical, and tropical zones alike.[1] But the flat-bottomed cirque is restricted to regions which are now, or have recently been, subjected to glaciation. Cirque-basins are familiar features in the Alpine lands of temperate latitudes, and they are met with likewise, but only at lofty elevations, in the warmer zones. When a mountain area was subjected to glaciation, the cirques, which occurred in immediate proximity to the snow-line, would form admirable reservoirs for the accumulation of snow and *névé*, and the formation of "summit glaciers." The shape of a cirque would greatly favour glacial erosion by enabling the ice to concentrate its grinding and disrupting action upon the point towards which the mountain-slopes converged. Hence, in time, the bottom of such a cirque could not fail to be ground out, and the basin thus formed, owing to the conditions that so specially favoured erosion,

[1] Although the true cirque usually presents the appearance of a niche-like indentation in a mountain-slope, not a few valleys terminate upwards in great amphitheatre-like cirques, the walls of which are often very steep. Such cirque-valleys appear now and again in our European mountains. As examples, may be cited the great cirque of Gavarni in the Pyrenees, the valleys of the Hallstädter See and the Königs See, and of the Trenta and the Wochein in the Alps, and the great cirque-valleys of Norway, such as that near Lunde (Jostedalsbrae), the precipitous encircling walls of which rise more than 3000 feet above the bottom of the valley. Glen Eunach (Cairngorm Mountains) is a good example of a Scottish valley with a cirque-shaped head. Such great cirque-valleys often contain lakes.

would tend to be relatively deeper than the rock-basins excavated in a broad mountain-valley.

The vertical distribution of corrie-basins in any given tract of mountains shows that they are closely related to former snow-lines. They occur in belts, or zones, and are not irregularly scattered over a whole region. Amongst the Scottish mountains two such zones can be recognised. In the lower part of these the corrie-basins range from 1500 feet to 2400 feet or thereabouts; in the upper they occur between 2400 feet and 3400 feet. Consequently, the two zones are met with together only among the most elevated mountain-groups. In the mountains of Middle Germany the zone of cirque-basins lies between 3000 feet and 3500 feet above sea-level; and Professor Partsch has pointed out the significant fact that the cirques, as we follow them from west to east, rise to higher and higher levels, showing, as he says, that the snow-line of glacial times gradually ascended as it passed eastward into the interior of the continent. Similarly in the Alps and the Pyrenees, cirque-basins occur in definite zones, and form harmonious systems in the several mountain-groups, each zone marking out a former snow- or *névé*-level.[1]

[1] Professor Penck gives the following table to show the relative heights attained by mountain-lakes—the zones of greatest development of high-level lakes. He includes in this table not only cirque-lakes, but many small barrier-lakes:

Norway	1000–1600 metres.
Hohe Tatra	1500–2100 "
Eastern Alps (Central Zone) . . .	1700–2800 "
Graubünden Alps	2000–2700 "

It is interesting further to note that in North and Middle Europe the cirque-basins affect chiefly the mountain-slopes that face the north and north-east. Thus of 78 in the uplands of Norway, according to Helland, 50 face the north, while 19 open towards the east. So, again, Partsch states that of 35 in the mountains of Middle Germany 19 look north and north-east, 13 east and south-east, and only 3 face the south and west. This distribution, as Penck remarks, is quite in keeping with existing conditions, for at present most snow accumulates on northern and eastern exposures. On southern exposures it quickly melts, while from the western declivities of the mountains it is blown away by the prevailing west winds.

2. *Mountain-Valley Basins.* This class includes all lakes of glacial origin occurring in mountain-valleys or closely connected with these. In some regions they are seen only at the very heads of the valleys, which may be cirque-shaped or not; elsewhere they appear towards the lower ends of the valleys, from which they now and again extend into the low grounds; or they may occur outside of the mountains altogether, opposite the mouths of great mountain-

Transylvanian Alps	1900–2100 metres
Pyrenees	1800–2400 "
Sierra Nevada (Granada) . . .	2900–3200 "
Himalaya	4000–5000 "
Sierra Nevada (S. Marta) . . .	3900–4000 "
Andes of Peru	4300–4600 "
Andes of Chili	1700–3000 "
New Zealand Alps	600–1200 "

valleys. Many of these are rock-basins, others are barrier-basins, that is, the water has been impounded by the unequal deposition of glacial and fluvio-glacial detritus. The large majority, however, partake of both characters; the lakes occupy rock-basins, the lower ends of which have been heightened by morainic and fluviatile accumulations. Many of the lakes in question attain a great depth. Amongst the lakes of the Alps, for example, we find depths of 469 feet (Zürich), 826 feet (Constance), 1013 feet (Geneva), 1135 feet (Garda), 1341 feet (Como), 2800 feet (Maggiore). Similar relatively deep lakes occur in Scotland. Loch Lomond, for instance, has an extreme depth of 630 feet, and Loch Ness of 780 feet.

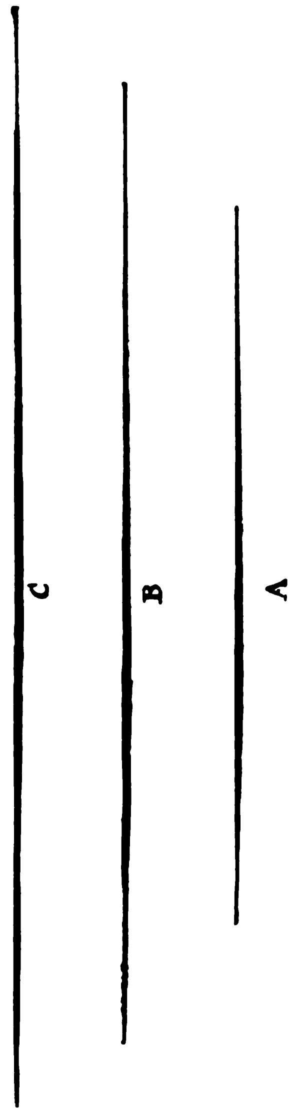

FIG. 85. LONGITUDINAL SECTIONS OF LAKE BASINS ON A TRUE SCALE.

A, length 130 times greater than the depth; *B*, length 176 times the depth; *C*, length 230 times the depth.

The mean depth of such lakes often approaches, and occasionally even exceeds, half of the extreme depth. But when we take into account the superficial area of the lakes, it becomes obvious that the basins they fill are mere shallow pans or troughs. The depth of Lake Como, for example, is only 130th part of its length; while the Lake of Geneva and Lake Garda are respectively 230 and 280 times longer than they are deep. Again, the length of Loch Ness is 136 times, and that of Loch Lomond 176 times greater than the depth.

The valley-basins of the Alps and other elevated regions of Europe are of relatively recent age. Not one is certainly known to be of older date than the Glacial Period. Further, they all lie within tracts which have been more or less severely ice-worn. Add to this the suggestive fact that they are distributed without any reference to the geological structure of the regions in which they appear. The late Sir A. C. Ramsay was the first to show that such basins had been excavated by glaciers. In the case of a glacier, as we have seen, erosion is carried on throughout the whole extent of its bed. It is obvious, however, that rock-grinding and rock-rupturing will proceed most actively under the thickest mass of the glacier, and the position of this thickest part will depend on the character of the valley and the number and size of the tributary glaciers. After the glacier has attained its maximum depth and speed its thickness progressively diminishes, and its rate of motion

at the same time gradually decreases as it flows on its way. Under these conditions a shallow trough must eventually be eroded in the bottom of the valley, the depth and extent of which will have a definite relation to the importance of the glacier. Towards the terminal part of the ice-flow erosion ceases, while accumulation there reaches its maximum, morainic *débris* and fluvio-glacial detritus being dumped upon and spread over the valley-bottom, the surface of which may thus be considerably raised. Hence, partly by erosion under the glacier, and partly by accumulation in the valley at and below its terminal front, a trough or basin is formed. On the disappearance of the glacier, a valley-lake comes into existence, the river escaping from which may by and by work its way down through the morainic and fluvio-glacial deposits, and thus gradually lower the level of the lake, until the rock-head is reached, after which the lowering of the level becomes a much slower process.

Valley-basins of the kind described occur, like cirque-basins, in determinate zones. Just as the latter indicate former *névé*-lines, so the former mark out the limits reached by valley-glaciers. In the loftier mountain tracts of temperate and northern regions, two or more zones of cirque-basins are found rising one above the other, each zone representing a former position of the *névé*-line. In like manner we have in the same regions corresponding zones of valley-basins, each of which marks a distinct stage of former glaciation. The basins in the lower reaches of the

valleys and at the base of the mountains belong to the period of maximum glaciation, when the snow-line descended to its lowest level; while the basins at or near the heads of the valleys are products of later epochs, when the snow-line had retreated to greater altitudes.

The valley-basins of a great mountain-range are typically developed where the valleys open freely upon the low grounds, for under such conditions the old glaciers, meeting with no obstructions, could readily creep outwards from their mountain-fastnesses and deploy upon the *Vorländ*.

Thus, in the case of the Alps, no barrier obstructed the outflow of the glaciers into Piedmont and Lombardy, and similar conditions obtained along the north front of the mountains east of the valley of the Aar. It is in those regions, therefore, that the lower valley-basins are best developed. The enormous sea of ice that flowed down the Rhone Valley, on the other hand, was dammed back by the opposing range of the Jura, and deflected to right and left. Hence the basins excavated by that great glacier differ to some extent from the typical valley-basins described above. Round the lower ends of the latter terminal moraines are usually more or less well developed. We look in vain, however, for such moraines circling round the lower ends of the Lake of Geneva or Lake Neuchâtel and the smaller lakes in its neighbourhood. The Neuchâtel basin has not been excavated by an ordinary valley-glacier in the usual way; it did

not come into existence under the lower reaches of such a glacier. Its position at the base of the Jura, and the direction of glaciation in its neighbourhood, show that it is a true *deflection-basin.* When a glacier is obstructed and turned aside from the path it would follow did no such obstacle intervene, the ice heaps up, and its erosive action, therefore, becomes intensified, so that a basin is eventually hollowed out in front of the opposing barrier. The basin occupied by the Lake of Geneva is of a more complex structure. The upper portion of the lake, which formerly extended up the valley of the Rhone as far as Bex, is comparable to one of the lakes of Lombardy; it is a mountain-valley basin. The northern half, however, is a deflection-basin, which, like the basin of Neuchâtel, owes its origin to the erosion induced by the barrier of the Jura, which caused a great heaping-up of ice between those mountains and the Alps.

Most of the rock-basins of the Alps have been more or less modified by fluviatile action. The levels of many lakes have in this way been raised, and the true character of their basins obscured. Were all the morainic and fluviatile accumulations in their neighbourhood to be removed, the area of some of the lakes would be considerably reduced.[1] On the

[1] It has been estimated that the surface of Lake Constance would fall 200 feet, and its area be reduced by a third, were the deposits which partially dam it up to be removed. So, in like manner, could we conjure away the superficial accumulations in the plains of Lombardy below Como, that lake would lose nearly 500 feet of its depth, and about half of its area.

other hand, not a few were formerly more extensive than they are now. Streams and rivers are gradually pushing their deltas forward into the upper reaches of a lake; and the same process takes place in other parts of the same basin opposite the mouths of lateral streams and torrents, so that in not a few cases lakes have been divided into two or more. Again, very many lakes have been entirely silted up.

We have spoken of the rock-basins which are so commonly encountered towards the lower and upper ends of mountain-valleys. It must not be supposed that glacially eroded basins occur nowhere else in mountain-valleys. Those referred to may, indeed, be taken as the normal types of valley-basins; each has been excavated under the lower reaches of a glacier, the lateral and terminal moraines and fluvio-glacial gravels of which usually appear in their immediate neighbourhood. Rock-basins, however, have been eroded elsewhere in the bed of a glacier, as in the case of the deflection-basins already described. These, as we have seen, owe their origin to the increased erosion caused by notable obstructions in the path of an ice-flow. It not infrequently happens that a mountain-valley becomes constricted owing to the mutual approach of its flanks; the valley-bottom expands and contracts as the opposing mountain-slopes recede or advance. When a valley of this character is occupied by a glacier it is obvious that each constriction must form an obstacle in its path, with the result that under the heaped-up ice erosion will be

intensified on the bed of the valley above the constriction, and a shallow basin will be ground out. On the disappearance of the glacier a lake will necessarily appear, and many such lakes occur in highly glaciated mountain tracts; frequently, however, lakes of this kind become silted up, and their former presence is then only indicated by flat sheets of alluvium. Again, it is well known that valley-basins of the normal type often show irregular depths, and it is not always easy to say how these have originated. Sometimes they are the result of valley constriction, sometimes of sudden changes in the direction of the valley, which have caused the ice to erode more energetically on one side than the other, for the line of most rapid motion in a glacier, as in a river, will shift from the centre to the side, or from side to side, with the windings of its course. Again, inequalities in the floor of a rock-basin may sometimes be due to the unequal resistance of the rocks. Nor must we forget that during its final melting a glacier might dump *débris* in a very confused fashion over its bed, while the subsequent deposition of alluvial matter swept into the lake at many different points by streams and torrents would similarly tend to produce inequalities.

But all valley-lakes, it must be remembered, are not rock-basins. On the contrary, not a few Alpine lakes, and many which occur in similar positions in the mountains of other lands, are true barrier-basins, dammed up wholly by morainic or by fluvio-glacial detritus, or by both. Again, numerous small lakes

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and pools occur in the cup-shaped and irregular depressions of the *paysage morainique* at the base of a mountain region. The moraines of this region mark the limits reached by the larger valley-glaciers. One of the most typical localities for the development of small morainic lakes of the kind referred to is the dreary district of the Dombes, in the valley of the Rhone. There, however, many of the pools are of artificial origin, and used as fishponds by the inhabitants. But it is the morainic character of the ground that makes this possible.

Thus the paths of the old valley-glaciers are frequently marked by the appearance of glacial lakes, large and small, and variously formed. Great valley-basins may be restricted to the mountains, or may extend for some distance into the *Vorländer*, or may occur wholly outside of the mountains. Most of these are rock-basins, but their depth has often been increased by accumulations of superficial materials. Other valley-basins are essentially barrier-lakes. Lastly, beyond the lowest valley-basins, generally well out upon the low grounds, we encounter the numerous pools and lakelets of the *paysage morainique*.

3. *Plateau and Lowland Basins.* The glacial basins we have hitherto been considering are products of the action of individual glaciers, small or great as the case may have been. They occur, therefore, either within mountain-valleys, or in their proximity. But over the wide tracts formerly invaded by the "inland

ice" of Northern Europe glacial lakes are not confined to mountain-valleys and the adjacent *Vorländer*, but are scattered broadcast over plateaux and lowlands. In those regions two areas of special lake-development may be recognised: (1) An area in which glacial erosion has been in excess of glacial accumulation; and (2) an area in which, conversely, accumulation has been in excess of erosion. In the former tracts *roches moutonnées* abound; the surface is thus often rapidly undulating. Low-lying, round-backed rocks extend on every side, while here and there the general monotony of the landscape is partly relieved by bare hills and now and again by bald mountain-heights, all scraped, bared, worn, and abraded by severe glacial action. In the countless dimples and irregular hollows of the surface lakes of all shapes and dimensions make their appearance, and the presence of innumerable bogs and marshes show further how many shallow sheets of water have been gradually obliterated. The most notable region of the kind in Europe is Finland, a land of lakes. But excellent examples occur in our own islands, such as the Outer Hebrides and the low-lying, rocky coast-lands of the tract lying between Loch Ewe and Loch Laxford. In North America the particular lake-lands of which we now speak are practically confined to and nearly co-extensive with the Dominion of Canada.

Of the basins developed in those regions some have been excavated, while others are barrier-basins.

The distribution of the former cannot always be satisfactorily explained. We may suppose that under a general ice-sheet some rocks would yield more readily than others. Some geologists are of opinion that certain rock-basins may be of preglacial origin, and that all the ice did was to plough out the alluvia with which such basins had been filled. The hollows themselves, they think, may have been caused by the weathering and rotting of rock, and the subsequent removal of the disintegrated materials by wind or other superficial agency. According to others the depressions may be tectonic basins filled up in preglacial times and only re-excavated by glacial action. Some of the larger lakes, such as Lakes Lodoga, Onega, and others in Northern Europe, and the Great Lakes of North America, almost certainly occupy tectonic basins, modified no doubt by considerable glacial erosion and accumulation. But the far more numerous small rock-basins of the regions now under review are unquestionably hollows of erosion. Some appear to have been ground out in places where the rocks offered less resistance to erosion, but probably the position of a larger number has been determined by the form of the ground. This is seen in the frequent appearance of rock-basins in places where the glacial current suffered constriction or obstruction. Thus in broken, hilly ground the thickness of ice and the rate of flow would vary from place to place, and unequal erosion of its bed would follow as a natural course. Not infrequently prominent obstructions

rose in its path, and in front of these deflection-basins were eroded, which usually extend in a direction at right angles to the trend of the ice-flow. If the obstruction were an isolated hill or mountain the hollow often assumed a horse-shoe shape, encircling the base of the hill. Much morainic *débris* was usually accumulated in the rear by such an obstruction, so as to form a long, sloping "tail." Again, valleys which have chanced to coincide in direction with the ice-flow not infrequently show a succession of two or more *constriction-basins.* In flat lands of tolerably even surface, however, deflection- and constriction-basins are wanting, the great majority of the lakes being drawn out in the direction of ice-flow. Although, owing to the presence of glacial and other superficial accumulations, we cannot always be sure whether such lakes rest wholly in rock-basins or not, there can be no doubt that they owe their origin to glacial action, partly to erosion and partly to accumulation. In the low grounds of Lewis (Outer Hebrides) the multitudinous lakes almost invariably tend to assume a linear direction, and by far the larger number are arranged along one or other of two lines, which strike as nearly as may be N.W. and S.E., and N.E. and S.W. respectively. Not infrequently one and the same lake shows both lines of direction, one portion of the water trending at right angles to the other. Nearly all the longest and most considerable lakes range from S.E. to N.W. This is the direction of glaciation, and the lakes having this particular

trend rest sometimes in true rock-basins, sometimes in hollows between parallel banks formed wholly of glacial deposits, or partly of these and solid rock. The north-east and south-west lakes, on the other hand, are drawn out more or less at right angles to the path of the old ice-flow. They follow precisely the line of "strike" (or general direction of the outcropping ledges or reefs of gneiss); when this direction changes there is a corresponding change in the trend of the lakes. Thus in places where the strike is east and west we have east and west lakes, which wheel round to south-west as soon as the strike shifts to that direction. In preglacial times the low-lying tracts of Lewis were in many places traversed by a series of rough ridges and interrupted escarpments, with intervening hollows corresponding to outcrops of the harder and the less resisting beds of gneiss. The dip of the rocks being generally south-east, the escarpments naturally faced the north-west. The inland ice, which subsequently overflowed this region from south-east to north-west, then advanced against the dip-slopes of the gneissose rocks, which were ground bare, while bottom-moraine was here and there deposited in front of the cliffs, knolls, and rocky ledges and ridges formed by the outcrops of the harder beds. Hence, when the ice finally disappeared, the hollows lying between parallel rock-ridges and escarpments were unequally coated with bottom-moraine, and an abundant series of longer and shorter troughs were thus prepared for the reception of water. The

north-east and south-west lakes are consequently barrier-lakes, dammed up wholly by boulder-clay or with rock and boulder-clay together. The manner in which the two groups of lakes now described frequently unite offers no difficulty. In many places the old strike-ridges have been cut across by the ice at right angles, and a new system of ridges and hollows has resulted. And it is not surprising, therefore, to find that not only lakes but also streams exhibit both directions, now trending north-west and south-east, and then turning sharply off at right angles to the course previously followed.

When we leave the highly abraded and ice-worn regions of *roches moutonnées*—the lands of multitudinous lakes and lakelets—we eventually enter upon tracts over which glacial accumulation has been in excess of erosion. Here lakes become much less numerous, and are met with only at intervals. Most of them extend over shallow depressions in the surface of the old ground-moraines, but a few occupy rock-hollows ground out in front of prominent obstructions. Lakes of the former kind were formerly much more plentiful, but owing to their limited depths many have been silted up, and are now replaced by alluvial flats. The deeper deflection-basins, on the other hand, have been more persistent as lakes, but they are comparatively few in number. Passing still farther outwards, and leaving behind the gently undulating and rolling plains, throughout which ground-moraine forms the dominant deposit at the surface,

we reach at last the *paysage morainique*, with its tumultuous hills, knolls, ridges, and embankments, and find ourselves once more in a region of lakes, or rather of lakelets, pools, and marshes. Among the most conspicuous examples of such a region is the *paysage morainique* of the last great Baltic glacier, extending from west to east through East Holstein, Mecklenburg-Strelitz, Uckermark, Neumark, Southern Pomerania, and the higher parts of West and East Prussia. Another well known region of similar character is the corresponding lake-dappled *paysage morainique* of North America, which embraces such vast tracts in the Northern States of the Union.

4. *Ice-Barrier Basins.* In existing glacier-regions ice-dammed lakes now and again appear. Of these the Märjelen See on the Aletsch glacier may be taken as an example. Their origin is simple enough. When a glacier advances across the mouth of a tributary valley, the stream flowing in the latter is dammed back, and a lake comes into existence. In the Alps lakes of this kind have formed from time to time, the sudden bursting of the ice-dams occasionally causing enormous devastation. In our own and other formerly glaciated countries the relics of such lakes—some of which must have persisted for long periods—are of not infrequent occurrence. The well known "Parallel-Roads" of Glen Roy are simply the beaches of an ice-barrier lake.

5. *Submarine Basins.* Here we are not concerned with the large and small basins that mark the

floor of the great oceanic troughs, all of which are doubtless tectonic. The hollows to which we would now refer are certain relatively smaller basins occurring in immediate proximity to the shores of recently depressed lands. The regions in which they appear, although submerged, form, nevertheless, a continuation of the continental plateau. The true border of the European continent, for example, extends in the north-west as far seaward as the 100-fathom line at least, and there is good ground for believing that within geologically recent times a large part, if not the whole, of that now depressed region existed as dry land. The sea-lochs of Scotland and the fiords of Norway simply occupy old mountain-valleys, while the numerous islets lying off those coasts and the British Islands themselves were all at one time connected and joined to the mainland of Europe. The basins to which we now call attention form two more or less well marked groups. One of these is practically confined to the fiords, the other is developed chiefly in front of islands that face the fiords.

Although it is not possible to go into much detail, it is nevertheless necessary to indicate the characteristic features of a typical fiord region. Norway, as we have already learned, is an ancient plateau, deeply incised and cut up, as it were, into irregular segments. These segments vary much in extent and form—sometimes the surface of the fjeld is flat and undulating, elsewhere it is scarped and worn into irregular groups and masses of variously shaped mountains and ridges

without any determinate arrangement. The orography is everywhere in strong contrast to that of the Alps, with their extended parallel chains and longitudinal valleys. Not less strong is the contrast between the fiord-valleys of Norway and the valleys of the Alpine chain. The latter in cross-section are commonly V-shaped, while the former are U-shaped. Again, fiord-valleys have relatively few lateral branches, the opposite being the case with the great valleys of the Alps, which are joined by numerous tributaries. Were the Alpine lands to be so submerged as to convert such valleys as the Rhone or the Inn into arms of the sea, it is obvious that numerous broad and long inlets would ramify right and left from these arms into the mountains. The fiord-valleys of Norway do not branch after that fashion; the hydrographic system of the country, as Professor Richter well observes, is imperfectly developed. The principal channels of erosion are the deep, trench-like fiord-valleys, the tributaries which reach these from the fjelds or plateaux being relatively insignificant. The main stream, flowing through a deep mountain-valley, has cut its way down to the level of the sea, which it enters at the head of a fiord. Below this point, however, few or no side valleys, as a rule, break the continuity of the fiord-walls. Numerous tributary waters, some of which are hardly less important than the head-stream, do indeed pour into the fiord, but they have not yet eroded for themselves deep trenches. After winding through the plateau-

land in broad and shallow valleys their relatively gentle course is suddenly interrupted, and they at once cascade down the precipitous rock-walls to the sea. The side valleys that open upon a fiord are thus truncated by the steep mountain-wall as abruptly, Dr. Richter remarks, as if they had been cut across with a knife.

Mountain-valleys of the V-shaped Alpine type are not wanting in the fjeld, but as they are followed inland towards the low water-partings of the plateau they soon lose their character and acquire softer features. The valleys of the fjeld-lands are for the most part broad and open, many lakes being scattered along the courses of the streams. We are here dealing, in fact, with a plateau lake-land, a region in which glacial erosion has been in excess of accumulation. It is through this gently undulating, highly iceworn plateau-land, with its shallow valleys, that the profound, chasm-like fiord-valleys have been cut to depths of 3000 to 6500 feet. That these enormous gorges are the work of erosion is not doubted by geologists, but the problem of their origin is nevertheless complex. Much has been written upon the subject, but no one has given a more lucid description of the actual facts, or a more intelligible explanation of their meaning, than Professor Richter, and him, therefore, we shall follow.

If we admit that a fiord is simply a partially drowned land-valley, and that the profound hollow in which it lies has been eroded by river action, how is it that the

side streams have succeeded in doing so little work? Why should the erosion of the main or fiord-valleys be so immeasurably in advance of that of the lateral valleys? Obviously there must have been a time when the process of valley formation proceeded more rapidly along the lines of the present fiords and their head-valleys than in the side valleys which open upon these from the fjelds. At that time the work of rain and running water could not have been carried on equally over the whole land, otherwise we should find now a completely developed hydrographic system—not a plateau intersected by profound chasms, but an undulating mountain-land with its regular valleys. Nor can we believe that the present distinctive features of fjeld and fiord originated contemporaneously under a general ice-sheet. The wild rock-walls of the fiords, mostly ice-worn though they be, are not glacial features. Ice does not carve out cañons. According to Dr. Richter, the remarkable contrast between the deep valleys of the fiords and the shallow side valleys that open upon them from the fjelds—the profound erosion in the former, and the arrest of erosion on the plateau—admits of only one explanation. While rivers and rapid ice-streams, flowing in previously excavated valleys, were actively engaged in deepening these, the adjacent fjelds were buried under sheets of *névé*. At the time the fiords assumed their present characteristic features, the snow-line must have been depressed below its existing level, and large glaciers, preceded by torrential rivers, must eventually have

flowed down the fiords to the submarine bars that now appear at or near their entrances. Such conditions obtained during certain stages of the Glacial Period, both before and after the epoch of maximum glaciation. While the fiords were being deepened, first by rivers and thereafter by large glaciers, the fjelds were undergoing effective glacial denudation, so that in time their configuration became greatly modified. The mountain-ridges with their regular hydrographic system, as developed in preglacial times, were by and by broken up and replaced by the undulating rocky and lake-dappled plateaux which we now see. In short, while rivers and glaciers were deepening the great valleys and making their walls steeper, the intervening mountain-heights were gradually being reduced and levelled by denudation. Underneath the firn and ice of the plateau the erosion of deep gullies was at a standstill. It was somewhat otherwise in the Alps, where the hydrographic system, perfectly regular in preglacial times, was only slightly modified by subsequent glacial action. Yet even there erosion proceeded most rapidly along the chief lines of ice-flow. Were the great rock-basins of the principal Alpine valleys pumped dry we should find the mouths or openings of the side valleys abruptly truncated, and their waters cascading suddenly into the ice-deepened main valleys. For, as Dr. Wallace has shown, it is the present lake-*surface*, not the lake-*bottom*, that represents approximately the level of the preglacial valley. In a word, erosion proceeded most

actively in the main valleys, the bottoms of which have been lowered for several hundred feet below the bottoms of the side valleys. Precisely the same phenomena are repeated in Scotland. Were all the water to disappear from the Highland lakes and sea-lochs, we should find waterfalls and cascades at the mouth of every lateral stream and torrent.

But another marked character of the fiords has yet to be mentioned. They are always deeper than the sea immediately outside, usually very much deeper. Some fiords show only one basin-shaped depression, while others may contain a succession of troughs. Frequently these basins are confined to the fiord, but in many cases they extend for less or greater distances beyond the entrance. In their form and disposition they are comparable to the great valley-basins of the Alps and similarly glaciated mountain tracts, and there can be little doubt that they have had a like origin. Were Scotland to be elevated so far as to run the sea out of her fiords, the latter would appear as mountain-valleys, each with one or more considerable lakes, in this and other respects exactly resembling the Highland glens that drain eastward into Loch Ness and the Moray Firth. The rock-basins in those glens, like the corresponding basins of the Alpine valleys, have often been modified by the accumulation of morainic *débris* and river-detritus at their lower ends. Many Highland lakes, in short, are deeper than they would be were all the superficial deposits in the glens to be removed. We

may well believe that the same is most likely to be true of the fiord-basins—the lips of the basins may in many cases be buried to some depth under morainic *débris* and more recent marine deposits. But that they are true rock-basins is shown by the fact that in not a few cases the sea-floor at the entrance is awash, ice-worn rocks every here and there rising to the surface and forming low islets and skerries. The fiord-basins in the depressed mountain-valleys of Scotland and Norway have obviously been ground out by large glaciers in the same way as the valley-basins of the Alpine lands. There are many other regions which show highly indented coasts, with long inlets stretching far inland, but these do not always contain basins. The latter only appear in places where large glaciers have formerly existed. Thus there are no fiord-basins in the Rias of Northern Spain, nor in the inlets of the Istrian and Dalmatian coasts, nor in the highly indented coast-lands of Australia and South-east China. But basins are always present in the ice-worn sounds of New Zealand, and in the true fiords of the higher latitudes of America. In a word, fiords are merely the drowned valleys of severely glaciated mountain tracts. A very slight depression of the land or rise of the sea-level would convert Loch Maree and Loch Lomond, and the great Alpine valleys that open upon the plains of the Po, into typical fiords.

Islands, as everyone knows, are scattered more or less abundantly along a fiord-indented coast. Dur-

ing the stage of maximum glaciation the glaciers, advancing beyond the fiords, coalesced in many cases to form a general ice-sheet which overflowed those islands in whole or in part. It is obvious that the steeper islands—those which rose more or less abruptly above the general level of the sea-floor—must have formed obstacles to the outflow of the *mer de glace*. Some of these mountainous islets were completely drowned in ice, while the tops of others soared above the level of the ice-sheet as *Nunatakkr*, only their less elevated portions being overwhelmed. On the sea-floor, in front of such islands we usually encounter more or less well marked depressions or basins, some of which attain a great depth. These are well indicated by the Admiralty's charts of our Scottish seas. We cannot, of course, tell whether those basins are wholly excavated in rock, or whether they may not owe some of their depth to unequal accumulation of glacial and marine deposits. But their form and disposition and the whole configuration of the sea-floor so exactly recall the aspect of the ice-worn low grounds of the Outer Hebrides, the rocky coast-lands of North-west Scotland, and the fjelds of Norway, that we can hardly doubt that the bottom of the Minch and adjacent areas owes its characteristic features to glaciation—that the deep troughs hugging the shores of the rocky islands that face the mainland are deflection-basins, ground out by the great *mer de glace* on its passage into the Atlantic.

CHAPTER XV

COAST-LINES

FORM AND GENERAL TREND OF COAST-LINES—SMOOTH OR REGULAR COASTS—INFLUENCE OF GEOLOGICAL STRUCTURE ON VARIOUS FORMS ASSUMED BY CLIFFS—CLIFFS CUT IN BEDDED AND IN AMORPHOUS ROCKS—SEA-CAVES—FLAT COAST-LINES AND COASTAL PLAINS—INDENTED OR IRREGULAR COASTS—GENERAL TRENDS OF COAST-LINES DETERMINED BY FORM OF LAND-SURFACE — SUBORDINATE INFLUENCE OF MARINE EROSION.

THE coast-lines of the globe—the varied forms they assume and the directions they follow—are an interesting study. Wandering alongshore and observing the effects of wave-action, we are soon convinced that here, as in landward areas, hard rocks and strong structures tend to resist erosion, while soft rocks and weak structures more readily succumb. When we so frequently find the former projecting seawards in capes and headlands, while the latter are often cut back in bays and inlets, it might almost seem as if both the shape and the direction of coast-lines had been determined solely by marine action. But this cannot be altogether true. If bays and all other inlets and arms of the sea were the result of

marine erosion alone, the most highly indented coasts should also be the oldest. If not, then they should occupy positions peculiarly exposed to the battering and undermining of waves and breakers, or they should be excavated in the softest and most yielding rocks. The very opposite of all this, however, is the case. Not only are highly indented coast-lines of relatively recent age, but they frequently consist of the hardest kinds of rock, and they are, moreover, not subject to wave-action in any greater degree than coasts which are smooth and regular. If indentations were always due to marine erosion, the sea should be still eating its way into the land at the head of most fiords, estuaries, and other inlets. Instead of advancing in such places, however, it is more frequently receding. Rivers entering the heads of estuaries and sea-lochs gradually push their deltas outwards. Not only so, but in long, narrow inlets and fiords waves and breakers do very little work—they are practically powerless. Since such inlets, therefore, are neither extended nor widened by the sea, they cannot owe their origin to its action. However potent an agent of erosion it may be, we cannot credit it with the formation of the numerous deep indentations of such a coast as that of Norway. In point of fact, the general tendency of marine erosion is to reduce irregularities—to cut back headlands, to silt up intervening bays, and to stretch banks and ridges across the mouths of estuaries and other notable indentations of the land, so as eventually to shut

these off more or less completely. Hence all coasts which can be shown to be of relatively great age have a gently sinuous or profusely curved outline. Conversely, as we have indicated, highly indented coasts are of recent origin—the sea has not yet had time to reduce their irregularities.

We must distinguish between the form and the general trend of a coast-line. The varying shape of cliff and low shore is no doubt largely determined by the manner in which the rocks yield to the sea, but the general direction followed by a coast obviously depends on the form of the land. If the latter be mountainous, with great valleys opening on the sea, the coast-line will usually be more or less deeply indented. If, on the other hand, it be a low-lying, gently undulating land, there will be a general absence of deep and long inlets, although broad and shallow bays may be numerous. Such a land may be margined by steep cliffs or it may be bordered by low plains, or by both. In short, however much the sea may modify the form of its coasts, it is evident that it has had but a small share in determining their direction. The latter obviously depends on the position of the sea-level and the shape of the land. Hence a very slight elevation or depression of the land would in many cases completely change the direction of the coast-lines. An elevation of 300 feet, for example, would lay dry the bed of the North Sea and the English Channel, while an elevation of 600 feet would not only join the British Islands to the

Continent, but cause the shores of Europe to advance some 50 or 60 miles beyond the Outer Hebrides and Ireland.

We shall first, therefore, treat of the various forms assumed by coast-lines, and thereafter the causes which have determined their general trends will be more particularly considered. When we run our eye over a map of the world we are struck by the fact that in some places the coasts are relatively smooth and unbroken, while in other regions they are more or less deeply indented. We have thus at least two principal types, which we may classify as (*a*) smooth or regular coasts, and (*b*) indented or irregular coasts.

Smooth or Regular Coasts. These may be high and steep, or low and gently shelving, the one kind often alternating with the other. Their chief characteristic is the absence of prominent inlets. A steep, regular coast, as shown upon a small-scale map, has a softly undulating or sinuous course, or presents a succession of smaller and larger curves. It need hardly be said that when such a long line of cliffs is examined in detail, many minor irregularities make their appearance. In some places the cliffs project boldly beyond the average coast-line to form headlands, elsewhere they curve backwards, or their continuity may be interrupted by more or less numerous creeks, gullies, and small inlets, which could only be represented upon a map of a very large scale. The cliffs, moreover, may vary in form at relatively short intervals, or they may preserve great uniformity of char-

acter for long stretches. All such inequalities and differences are due to the nature of the rocks and the mode of their arrangement. Bedded rocks, for example, owing to the regularity of their joints, tend to form cliffs with even faces. If the strata be horizontal, it is obvious that the cliffs must be vertical, or nearly so, since the rocks naturally yield along their approximately vertical division-planes. When a slice has been detached from the cliff, the new surface exposed is an even wall of rock. But as the beds entering into the formation of such a cliff are likely to yield unequally to weathering, the smooth wall of rock sooner or later becomes etched and furrowed. (Fig. 86.) Now and again, however, owing to the

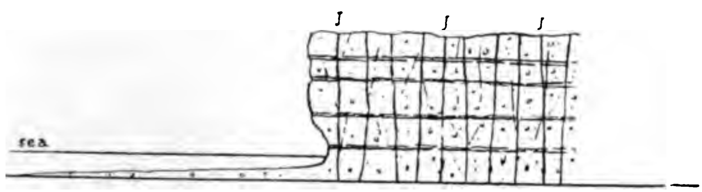

FIG. 86. SEA-CLIFF CUT IN HORIZONTAL STRATA.
jj, joints.

nature of the rocks, or to the rapid retreat of the cliffs, weathering has not sufficient time to effect any marked modification of the surface. When the strata, instead of being horizontal, are inclined, and the dip is inland, or away from the coast, the joint-planes necessarily have an inclination towards the sea, and the cliffs naturally slope in the same direction. (Fig. 87, p. 320.) On the other hand, should the strata

dip seaward, cliffs hewn out of them have a tendency to overhang, because the division-planes along which

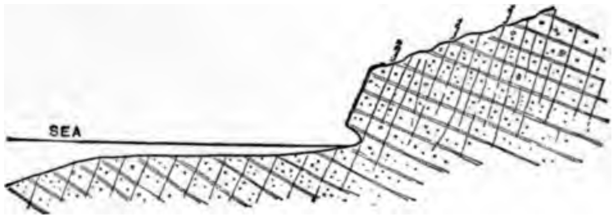

FIG. 87. SEA-CLIFF CUT IN STRATA DIPPING INLAND.
jj, joints.

the rocks yield are now inclined away from the shore. (Fig. 88.) Cliffs having this structure are in a state of unstable equilibrium—the truncated beds being apt to slide forward—so that actually overhanging

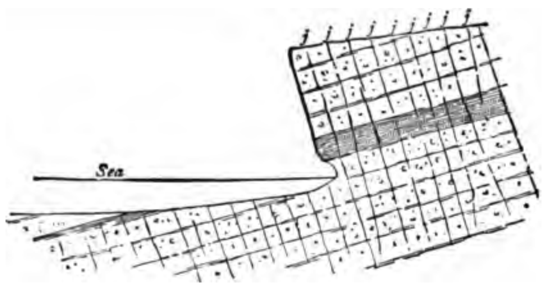

FIG. 88. SEA-CLIFF CUT IN STRATA DIPPING SEAWARD.
jj, joints.

cliffs of this kind are not often met with. Not infrequently, indeed, when strata dip seaward at a relatively low angle they form natural breakwaters, and the waves do not succeed in cutting out a cliff.

In all cases, when the strike of the strata coincides

approximately with the trend of a coast-line—the dip being either seaward or landward—the forms assumed by cliffs are largely determined by the position of the strike-joints. The regularity of a line of cliffs is likewise greatly controlled by the position of the dip-joints, which, it will be remembered, cut the strike-joints at approximately right angles. If the former be somewhat wide apart, and not strongly pronounced or discontinuous, the sea-wall may run continuously for miles without any marked interruptions. On the other hand, should the dip-joints be in places more numerous and closely set, they will form lines of weakness, and thus allow the waves to sap and notch the cliff, so that all such cliffs tend to assume rectangular outlines, the faces of the sea-wall and the indentations that break its continuity being determined by the double set of joints. And the same holds true in the case of horizontal strata.

It goes without saying that the cliffs of a regular coast are evidence of marine erosion. The sea acts like a great horizontal saw, forming rock-shelves and terraces that increase in width as the cliffs are undermined and cut back. So effectually has the work been done in many cases that at high tide these terraces of erosion are completely covered. Frequently, however, islets, stacks, and low reefs and skerries appear—fragments of land which owe their preservation to the superior hardness of the rocks at the sea-level, or to some peculiarity of structure, such as the paucity or absence of joints. Lofty stacks are

perhaps most commonly met with in the case of horizontal or approximately horizontal strata, or of gently inclined beds, when the strike coincides with the general trend of a sea-wall. But smaller stacks, reefs, and skerries are usually most abundant when the coast-line cuts across the strike, and the truncated rocks differ much as regards durability. Such a coast-line is usually very ragged or frayed out. The cliffs are often approximately vertical, but usually show many narrow and broader indentations, while long parallel ranges of reefs, skerries, stacks, and islets diversify the surface of the terrace of erosion.

Of the various forms presented by the projecting bastions and towers of a line of cliffs, and by the islets and stacks of the sea-shelf, it is not necessary to say more than that these necessarily vary with the nature of the rocks and the geological structure. In the case of horizontal strata they all have a tendency to assume pyramidal or conical shapes, and similar forms are usually seen in the cliffs of massive structureless accumulations like boulder-clay. Stacks built up of inclined strata are usually less regular in form. With a low dip the truncated beds are necessarily unstable, and the tendency to collapse is greater than it is in the case of a horizontal arrangement. But with a high dip the structure becomes more resisting, especially if the beds be thick and massive. When the strata are folded we not infrequently find that projecting headlands, islets, and stacks coincide with synclinal arrangements. In short, it may be said

generally that the geological structures which best withstand the action of the eroding agents in mountainous and inland regions are just those which offer the most resistance to the assaults of waves and breakers. Finally, it must be borne in mind that the action of the sea in the reduction of a steep coast-line is always more or less aided and modified by other epigene agents. Were it not for the action of springs and frost coast-cliffs would often be steeper and more abrupt than they generally are, the tendency being for cliffs of all kinds of structure to become benched backwards. Overhanging and absolutely vertical rock-walls are by no means so common as one might suppose; however steep a cliff may be, it usually has an inclination seawards. The accompany-

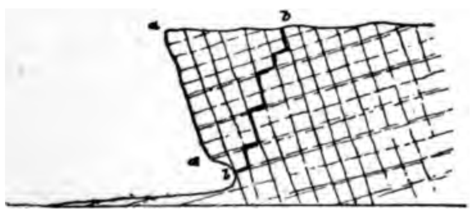

FIG. 89. SEA-CLIFF CUT IN BEDS DIPPING SEAWARD.

a a, cliff-face determined by master-joint; cliff may yield along several joints in succession, as at *b—b*.

ing diagram, representing strata dipping seawards, shows how a cliff may be overhanging or not according as the beds yield in a wholesale fashion along one joint-plane, or bed by bed along different joint-planes. The cliff-face *a—a* coincides with a master-joint. It is obvious, however, that yielding may take place ir-

regularly along different joints, and we may have the overhanging cliff benched back and replaced by the sloping face *b—b*.

Massive crystalline igneous rocks yield forms of cliff that offer strong contrasts to cliffs excavated in bedded strata. Owing to inequalities in their composition, texture, and structure, and to the frequent irregularity of their joints, they are prone to assume particularly rugged, broken, and bizarre forms, amongst which we may look in vain for any trace of the rectangular outlines so commonly present in the case of bedded rocks. The faces of the cliffs are very rarely approximately even, but vary indefinitely, the harder and more sparingly jointed portions projecting, it may be, to form buttresses and bastions, while the softer and more shattered portions are eaten away and replaced by coves and gullies. Now and again, however, when the joints are more regular, as in the columnar structure of many basalts, etc., and the approximately rectangular joints of certain granites, mural cliffs may appear. The crystalline schists, again, exhibit every variety of feature. But inasmuch as their bedding is usually more or less highly inclined or contorted, and their jointing is irregular, they do not often show the rectangular forms that are characteristic of cliffs hewn out of sedimentary strata. Their coast-lines are usually as steep and rugged as those of massive crystalline rocks, but they present greater variety of forms, the alternation of different kinds of schist and the highly inclined, curved, or contorted bedding, and ir-

regular joints often giving rise to most complex and peculiar features. Rugged stacks and skerries are very commonly present when either massive crystalline rocks or schists form the coast-line.

Of the formation of caves by marine action we have already spoken. Caves are not confined to any one kind of rock or rock-structure, and naturally vary in form and extent with the character and the arrangement of the masses in which they are excavated. When the rocks at the base of a sea-cliff are of unequal durability the undermining action of the waves and breakers must result either in the formation of caves or in the irregular retreat of the sea-wall. Much will depend on the character of the rocks above the reach of the tide. Should these be massive and not traversed by many joints, the conditions will be favourable for the formation of large caves. It is obvious, however, that if well marked joints be plentifully present the rocks cannot be undermined to any extent before collapse takes place.

We may now very shortly consider the appearances presented by flat or gently shelving, regular coast-lines. As a rule these are softly sinuous, showing a succession of broad, evenly curved bays separated usually by low capes and headlands. Shores of this character are often bordered by banks of beach-gravels and sand-dunes, behind which not infrequently appear salt-water or brackish-water lagoons. In the absence of the latter we may have a coastal plain traversed by parallel series of old beach-gravels and

sand-dunes. Such coastal plains obviously owe their origin to the action of streams and rivers, and are typically represented by those great deltas which we have referred to in an earlier chapter as examples of plains of accumulation. But the material carried by rivers to the sea does not always accumulate opposite their mouths. Tidal currents often prevent the rapid growth of deltas by sweeping much of the material away and depositing it alongshore, so as to form gradually a far-extended coastal-plain. The low plains that fringe the Atlantic shores of the Southern States of North America consist in this way of the sediment brought down by numerous streams and rivers, collected and redistributed by the sea. Indeed, of coastal-plains generally it may be said that they are either directly or indirectly of fluviatile origin. The delta of a great river is the direct product of river-action. Immense quantities of alluvial matter, however, are swept down to sea, and accumulate upon the bottom at no great distance from the shore. Should a negative movement of sea-level take place, a narrower or broader belt of sea-floor then becomes dry land, the new coastal plain having been built up chiefly of sediment washed down by streams and rivers. Coastal plains are thus not infrequently the result of crustal movements. As showing the dependence of coastal plains upon the activity of rivers, Professor Penck has pointed out that such plains are invariably absent from coasts to which no considerable streams and rivers descend.

In fine, as regards regular coast-lines, we see that they are not fixed, but oscillating, retreating in some places, advancing elsewhere. Cliffs, stacks, and skerries show us where the land is losing, and coastal plains where it is gaining. Much sediment washed down from the land comes to rest in quiet bays, and these in time tend to be filled up. We note also how detritus derived from cliffs and rocky headlands is apt to be swept by tidal currents into the same quiet receptacles. Thus, while cliffs retreat, the flat shores of adjacent bays often advance, until a definite relation between the steep and low coasts has been established. When at last the coast-line presents, in the words of Reclus, "a series of regular and rhythmical curves," it may become relatively stable. But by the continuous descent of sediment from the land and its accumulation along low shores, and by the gradual retreat of cliffs elsewhere, complete stability is impossible.

Indented or Irregular Coasts. When we consider the surface of the earth's crust as a whole we recognise two great areas, an oceanic depressed region and a continental elevated region, or, shortly, an oceanic basin and a continental plateau. The larger land-masses are all situated upon, but are nowhere co-extensive with, this plateau, considerable portions of which are under the sea-level. In regions where existing coast-lines approach the margin of the continental plateau, they are apt to run for long distances in one determinate direction, and, whether the coastal

land be high or not, to show a gentle sinuosity. Their course is seldom interrupted by bold headlands or peninsulas, or by long intruding inlets, while fringing or marginal islands rarely occur. Where, on the other hand, the coast-line retires to a great distance from the edge of the oceanic basin, its continuity is constantly interrupted, and fringing islands usually abound. Thus the coast-lines of West Africa owe their freedom from deep indentations, their continuous direction, and general absence of fringing islands, to their approximate coincidence with the steep boundary-slopes of the continental plateau. Conversely, the irregularities characteristic of the coast-lines of North-west Europe, and the corresponding latitudes of North America, are determined by the superficial configuration of the same plateau, which in those regions is relatively more depressed. In a word, coast-lines are profusely indented or not according as they recede from or approach the edge of the continental plateau. Hence all highly indented coast-lines are evidence that the land is sinking, or has recently sunk, the directions of the coast-line depending on the form or configuration of the submerged land. If the region be devoid of river-valleys, as most desert areas are, the coast-line will show no prominent indentations. If, on the other hand, it be well watered and mountainous, its shores will be interrupted by more or less numerous narrow inlets running often far into the land, while peninsulas and fringing islands will probably abound. The fiord-

coasts of the higher latitudes of both hemispheres are typical examples of the kind. Indeed, we may say that irregular coasts are dominant in the higher latitudes, while smooth coasts are more characteristic of lower latitudes. Irregular coast-lines, however, are by no means restricted to high latitudes, but are met with in every zone. They abound in the Mediterranean: the whole east coast of Asia is more or less deeply indented and margined by islands, large and small; Australia, Madagascar, Brazil, the Isthmus of Panama, and many other tropical and subtropical lands, show in places more or less deeply indented coast-lines. So widely distributed, in short, are such coast-lines that the present would appear to be a period rather of depression than of elevation. It is true that in the fiord-coasts we usually meet with evidence to show that the land has recently risen, but much greater uplift would be required to restore those regions to their former level.

Indented or irregular coasts are thus not the result of marine erosion. The fiords of high latitudes and the narrow inlets of non-glaciated lands are simply submerged land-valleys; the intricate coast-lines of such regions have been determined by preceding subaërial denudation. The general trend or direction of the coasts everywhere, therefore, is the result of crustal movements, the actual form or character of the coast-line, its regularity or irregularity, depending very largely on its position with reference to the true margin of the great continental plateau. In all

regions where the marginal areas of that plateau are depressed we find a highly indented seaboard and numerous fringing islands. Such is the case, as already remarked, in the northern latitudes of North America and Europe, and the phenomena there are repeated in the corresponding latitudes of South America. Again, the manifold irregularities of the coasts of South-eastern Asia, and the multitude of islands between that continent and Australia and New Zealand, are all evidence that the surface of the continental plateau in those regions is extensively invaded by the sea. On the other hand, where existing coasts approach the margin of the plateau, they are, upon the whole, more regular, showing few or no important indentations or fringing islands. The actual margin, however—the zone where continental plateau and oceanic basin meet—is somewhat unstable and liable to movements of elevation and depression. Where the latter kind of movement has recently occurred, therefore, inlets and gulfs make their appearance, as at Rio Janeiro, on the coast of Brazil. Movements in the opposite direction, however, by laying bare the crustal shelf of marine erosion and sedimentation, only produce a flat and regular shore-line.

In fine, then, when we consider the geographical development of our lands and their coast-lines, we must admit that crustal movements have played a most important *rôle.* But the inequalities of surface resulting from such movements are universally modified by denudation and sedimentation. Table-lands

and mountains are gradually demolished, and the basins and depressions in the surface of the great continental plateau become slowly filled with their detritus. Thus inland seas and lakes tend to vanish, inlets and estuaries are silted up, and the land in places advances seaward. To the action of rain and rivers that of the sea is added, so that by the combined operation of all epigene agents the irregularities of coast-lines tend to become reduced. This is best seen in regions where the seas are comparatively shallow—where the coast-lines are withdrawn for some considerable distance from the edge of the great oceanic depression. In such shallow seas sedimentation and erosion proceed apace. But when the coast-lines are not far removed from that depression, they are necessarily washed by deeper waters, and become modified chiefly by erosion.

"Should they preserve that position for a prolonged period of time, they will eventually be cut back by the sea. In this way a shelf or terrace will be formed, narrow in some places, broader in others, according to the resistance offered by the varying character of the rocks. But no inlets or fiords can result from such action. At most the harder and less readily demolished rocks will form headlands, while shallow bays will be scooped out of the more yielding masses. In short, between the narrower and broader parts of the eroded shelf or terrace a certain proportion will tend to be preserved. As the shelf is widened sedimentation will become more and more effective, and in places may come to protect the land from further encroachment by the sea. All long-established coast-lines thus acquire a characteristically sinuous form."

"To sum up, then," as we have elsewhere remarked, "the

chief agents concerned in the development of coast-lines are crustal movements, sedimentation, and marine erosion. All the main trends are the result of elevation and depression. Considerable geographical changes, however, have been brought about by the silting-up of those shallow and sheltered seas which in certain regions overflow wide areas of the continental plateau. Throughout all the ages, indeed, epigene agents have striven to reduce the superficial inequalities of that plateau by levelling heights and filling up depressions, and thus, as it were, flattening out the land-surface and causing it to extend. The erosive action of the sea, from our present point of view, is of comparatively little importance. It merely adds a few finishing touches to the work performed by the other agents of change."

But if it be true that all the main trends of our coast-lines are the result of crustal movements, it is no less true that many of the indentations that break the continuity of an otherwise regular coast-line are often due to the same cause. The general trend of the coast-line of South America, for example, from Pernambuco to the mouth of the River Plate, coincides with the direction of the continental plateau, and may be said, therefore, to have been determined by crustal movements. The shores, however, have been greatly modified by sedimentation, and to a less extent by erosion, while the numerous indentations and islets at and near Rio Janeiro are evidence of recent depression. In a word, it holds true for all the coast-lines of the globe that not only their general direction, but their more or less numerous indentations, are the result of crustal movements. Estuaries, fiords, and inlets generally are merely the seaward prolongations

of valleys and other hollows of the land. The indentations due to marine erosion are relatively so insignificant, that they can be rarely expressed upon a map of small scale. It is the form of the land that determines the character of a coast-line. An indented coast-line is the result of depression; a smooth, flat shore with no indentations is more usually, although not always, due to elevation or sedimentation. But a featureless desert-land, smoothed out by æolian erosion and accumulation, would necessarily be bounded by an even coast-line, whether that coast-line were the result of upheaval or depression. Finally, the coast-lines of regions which have remained for a long time undisturbed by crustal movements tend, as we have seen, to assume a special form. Erosion and sedimentation in this case combine to produce "a series of regular and rhythmical curves."

We have made no reference to the interesting fact that plants and animals play a certain part in the formation of coast-lines in some regions. This is only conspicuous, however, in tropical and subtropical latitudes. The mangrove-tree, for example, which flourishes along the margins of low, shelving shores, forms dense belts of jungle, which continue to extend seaward until the depth becomes too great. Some of these jungles attain a width of ten or even of twenty miles, and are in places rapidly extending. Professor Shaler is inclined to think that on the coast of Florida the trees may advance over the sea-floor at the rate of twenty to thirty feet in a century.

The closely set roots and rootlets bring about the deposition of sediment, and flotsam and jetsam of all kinds become entangled, so that eventually a low mole is formed along the swampy shore, which bars the escape of rain-water towards the sea, and thus marshes capable of supporting fresh-water plants and various bushes and trees come into existence.

In other warm seas coral plays a not unimportant part in the formation of new lands. Fringing-reefs, barrier-reefs, and atolls are of great interest from many points of view, but into the history of their formation we need not enter. It is enough to recognise the fact that shore-lines now and again owe their very existence to organic action.

CHAPTER XVI

CLASSIFICATION OF LAND-FORMS

PLAINS OF ACCUMULATION AND OF EROSION—PLATEAUX OF ACCUMULATION AND OF EROSION—HILLS AND MOUNTAINS; ORIGINAL OR TECTONIC, AND SUBSEQUENT OR RELICT MOUNTAINS—VALLEYS; ORIGINAL OR TECTONIC, AND SUBSEQUENT OR EROSION VALLEYS—BASINS—COAST-LINES.

WE have now passed in rapid review the more salient and notable features of the land-surface, and have discussed the several causes of their origin. The present chapter may therefore be devoted to the classification of those features, and will serve as a general summary of the results arrived at.

The leading features to be recognised are plains, plateaux, hills and mountains, valleys, basins, and other hollows and depressions of the surface, and, lastly, coast-lines.

1. *Plains.* These are areas of approximately flat or gently undulating land. It is needless to say, however, that plains almost invariably have a general slope in one or more directions. This, however, is so gentle, as a rule, that it is hardly perceptible. They are confined to lowlands; but now and again,

in the case of very extensive areas, the surface of a plain rises inland so imperceptibly that it may attain an elevation eventually of several thousand feet. This, however, is exceptional. Elevated flat lands are usually termed plateaux. Two kinds of plains are recognised, viz., *plains of accumulation* and *plains of erosion*. A plain of accumulation is built up of approximately horizontal deposits, so that the external surface is a more or less exact expression of the internal geological structure. All such plains tend to become modified by epigene action. If the plain be at or near a base-level of erosion, rain and running water have little effect upon it, but under certain conditions the surface may be considerably modified by the action of the wind. If the plain be traversed by a great river, or margined by the sea or by an extensive lake, sand-dunes may invade it more or less abundantly. Many coastal plains, indeed, have been formed partly by aqueous sedimentation and partly by the activity of the wind blowing sand before it from the exposed beaches. The higher a plain rises above its base-level the more it is subjected to aqueous erosion, and the more irregular and undulating does its surface become, the nature of the materials of which it is composed having no small influence in determining the character and extent of the denudation. Other things being equal, a plain consisting chiefly of impervious argillaceous deposits is more readily washed down than one built up largely of sand, shingle, gravel, and other more

or less porous materials. Many plains of accumulation are among the richest and most fertile tracts in the world, while others (and these are usually the most extensive) are relatively infertile, not a few being more or less destitute of vegetable covering. Among European plains of accumulation may be mentioned the French Landes, the far-extending flats of the Low Countries, and the grassy Steppes of Hungary and Russia. The arid wastes of the Aralo-Caspian depression and the broad Tundras of Siberia, the Prairies of North America, and the Llanos and Pampas of South America, are all more or less plains of accumulation—their approximately flat or gently undulating surface is due directly either to aqueous sedimentation or to wind-action, or to both.

Not infrequently, however, the superficial accumulations of such tracts are of no great thickness, but spread over and conceal old plains of erosion. A *plain of erosion* is distinguished by the fact that its surface does not necessarily coincide with the underground structure. It is only when the plain has resulted from the levelling of a series of horizontal strata that external form and internal structure can agree. In the great majority of cases no such coincidence occurs. The plains in question may consist either of horizontal or slightly inclined and gently undulating, or highly folded and contorted, strata, or they may be composed largely or wholly of igneous or of schistose rocks. They are the base-levels to which old land-surfaces have been reduced; they re-

present the final stage of a cycle of erosion. Occurring as they usually do in lowlands, they are liable to become covered with alluvial and other deposits, and thus at the surface often show as plains of accumulation. Now and again they have been submerged and more or less deeply buried under marine sediments, and thus when re-elevated the new-born lands present the appearance of plains of accumulation. Probably the great majority of the latter are merely superimposed on pre-existing plains of erosion. The wide low-lying tracts through which the larger rivers of the globe reach the sea are often plains of erosion more or less covered or concealed under alluvial deposits.

2. *Plateaux or Table-Lands.* No hard-and-fast line can be drawn between plains and plateaux. The term plateau, however, is usually applied to any flat land of considerable elevation which is separated from lowlands by somewhat steep slopes. When a plateau is built up of horizontal beds it is described as a *plateau of accumulation*—external form and internal structure coinciding. When such is not the case, when the arrangement of the rocks and the general shape of the surface do not agree, we have what is termed a *plateau of erosion.* In a word, plateaux are simply elevated plains. But, standing as they do at a higher level, they are necessarily subject to more active and intense erosion, and, according to their age, are correspondingly more deeply incised and abraded. Plateaux of all kinds eventually become

cut up into segments, and these progressively diminish in extent as erosion proceeds. Every table-land, in short, tends to acquire an irregular mountainous aspect. As examples of highly eroded plateaux of accumulation may be cited the Plateau of the Colorado, the Uplands of Abyssinia, and the Deccan of India. Plateaux of erosion, as might have been expected, are far more common, many excellent examples occurring in our own continent, such as the highly denuded plateaux of Scandinavia and Scotland and the plateau of Central France.

3. *Hills and Mountains.* Just as we cannot separate plains from plateaux by any hard-and-fast line, so we find it impossible to distinguish clearly between hills and mountains. In general we may say that the term *hill* is properly restricted to more or less abrupt elevations of less than 1000 ft., all the altitudes exceeding this being *mountains*. The terms, however, are loosely used, for in very lofty mountain regions eminences considerably above 1000 ft. are spoken of as hills, while in low-lying tracts heights of only a few hundred feet not infrequently become dignified with the name of mountains. It is obvious, in short, that just as plains merge into plateaux, so there must be a gradual transition from hills into mountains. For purposes of classification, therefore, it is not necessary to distinguish between the latter, and we shall treat of them both under the common head of mountains. From our present point of view, then, a mountain is simply a more or less abrupt elevation,

or somewhat sudden increase in the slope of a land-surface, and may be of any height from less than one hundred feet upwards. It may also be of any extent, and either isolated or more or less closely associated with other elevations, forming regular or irregular groups or definite ranges. Notwithstanding the great differences of elevation, of form, and of arrangement of hills and mountains, it is obvious that all these fall naturally into two divisions, namely, (*a*) elevations which have been formed as such either by epigene or by hypogene action, and (*b*) elevations which have been carved out of pre-existing rock-masses by epigene action alone. To avoid periphrasis, we shall speak of these two kinds of elevations as *original* or *tectonic mountains*, and *subsequent* or *relict mountains*, respectively.

(*a*) *Original or Tectonic Mountains.* Under this head come many of the most insignificant as well as the majority of the greater elevations of the globe. Some of these have been piled or heaped up at the surface—they have grown into heights by gradual accumulation, and may therefore be termed *accumulation-mountains.* This group naturally includes all volcanic cones and hills, geyser mounds, mud-volcanoes, etc. Many of these, no doubt, are mere monticles and hillocks, but all alike owe their origin to the extrusion of materials from below and the accumulation of these at the surface. Of much less importance are the eminences formed by the direct action of epigene agents, hardly any of which ever reach the

height and dimensions that are usually associated with the term mountain. Nevertheless, they form not infrequently conspicuous land-features, and cannot be ignored in our classification of land-forms. Among them are included morainic and fluvio-glacial hills and ridges of every kind, sand-dunes, etc.

But by far the most important tectonic mountains are those which have resulted from the flexuring and fracturing of the earth's crust,—*deformation-mountains*, as they may be termed. All the great mountain-ranges of the globe come under this group. The majority of these owe their origin essentially to tangential pushing and crushing; they consist for the most part of flexed and contorted rocks. Now and again, however, we meet with mountain-ranges the rocks of which may show no conspicuous folds and flexures. Ranges of this kind have been determined by series of great parallel fractures and dislocations of the crust; the ranges are, in short, vast rectangular blocks of strata which may not otherwise be much disturbed. The Alps, the Himalayas, and the Cordilleras of America are typical examples of deformation-mountains composed of highly folded rocks. Dislocations are, of course common enough among such chains and ranges, but their distinguishing character is the folding and contortion—hence they are termed *folded* or *flexured mountains.* The faulted ranges of the Great Basin (North America) are notable examples of the other kind of deformation-mountains. In these ranges the strata are sometimes

horizontal, or approximately so, but are more usually inclined. Folding and flexing may be absent, or only partially and locally developed. The characteristic features of such ranges are the great faults that bound them, and hence they may be spoken of as *dislocation-mountains.* In the same category would come the *Horste* of German geologists. These are mountains bounded by dislocations—they project above the general level because the rocks surrounding them have been dropped down by faulting. Under the head of deformation-mountains we may also include those gibbosities, or prominent swellings of the surface, caused by the intrusion below of masses of molten matter. They are typically represented by the Henry Mountains of Utah and the Elk Mountains of Colorado, and may be termed *laccolith-mountains.*

Of course, all deformation-mountains are more or less denuded, some of them to such an extent that their original configuration can only be guessed at. But since they owe their elevation above adjacent lowlands to crustal movements, they are entitled to be classed as tectonic mountains.

(*b*) *Subsequent or Relict Mountains.* Mountains belonging to this great class frequently form irregular groups,—there is often an absence of arrangement in separate parallel or interosculating ridges and ranges such as characterises tectonic mountains. This absence of alignment or orientation, however, is by no means general, and is most characteristic of relict

mountains which have been carved out of horizontal and gently undulating strata, the strike of which is constantly changing. When the strike runs persistently for long distances in one direction, the mountains in such a region now and again form more or less parallel ranges, having the same trend as the strike.

The direction and to a large extent the shape or form of relict mountains are thus mainly determined by the geological structure. They are the more salient portions of plateaux which are in process of being reduced to some base-level of erosion. Plateaux of accumulation are eventually cut up into segments, which, progressively diminishing in extent and height, form irregular groups of tabular and pyramidal hills and mountains. Hills and mountains hewn out of plateaux of erosion, on the other hand, not infrequently simulate the arrangements that are most characteristic of deformation-mountains. Should the strata consist of a thick series of relatively soft rocks, with here and there interbedded rocks of a less yielding kind, all dipping at a moderate angle in one direction, the outcrops of the harder rocks eventually come to project prominently. We thus have long lines or ranges of escarpments, separated from each other by parallel hollows. When the strata dip at a high angle, however, the outcrops of the harder rocks often form series of narrower and broader ridges, rather than well-marked escarpments and dip-slopes, but the ridges continue to be separated by strike-valleys. Even when the rocks of a plateau are highly contorted and

schistose, they nevertheless sometimes tend to be carved into ridges and ranges, marking the outcrops of the less readily reduced masses. More frequently, however, owing to the direction given to the drainage by the original slopes of the surface, or to the uniform character of the rocks, or, it may be, to complex geological structure, all trace of any definite linear arrangement disappears—parallel ranges and intervening hollows are replaced by amorphous groups of heights and irregularly diverging or radiating valleys. This is frequently due to the presence of great masses of plutonic rocks, such as granite. Igneous intrusions of one kind or another, indeed, often play a not unimportant *rôle* in giving variety to the surface of such regions. Lastly, we may note that when the flexured rocks of a plateau are arranged in symmetrical folds, the synclines, by offering greater resistance to denudation than the adjacent anticlines, tend to be developed into *synclinal mountains.*

As examples of tabular and pyramidal relict mountains we may cite the Red Sandstone Hills of Sutherland, Ingleborough in Yorkshire, the picturesque and often fantastic hills of Saxon Switzerland, the basalt-heights of the Faröe Islands and Iceland, and the buttes and mesas of the Colorado Plateau. Throughout the Lowlands of Scotland we meet with diversified features, all the elevations being of subsequent formation, or the result of denudation. The Lowlands are, in short, a plain of erosion, the surface of which has been greatly modified by epigene action. The

more prominent knolls, hills, heights, and ranges of all kinds mark the outcrops of the relatively hard rocks, which in most cases are of igneous origin. Many of the isolated knolls and abrupt eminences are the *necks* of ancient volcanoes, and these are usually scattered irregularly without reference to the dip of the surrounding strata. Most of the bolder crags and escarpments, however, are formed by the outcrops of sheets and beds of basalt, etc. As the dip is continually changing, such escarpments face almost every point of the compass. When the strike is more persistent the outcrops of volcanic and intrusive rocks often form considerable ranges, such, for example, as the Ochils, the Sidlaws, the Pentlands, the Bathgate Hills, the Campsie Hills, and others. All these heights might be termed *escarpment-hills.* So again the outcrops of the calcareous Mesozoic strata of England form still more persistent ranges of escarpment-hills, traversing the country from N.N.E. to S.S.W. The Moors and Wolds of Yorkshire, the Cotswolds, the Chiltern Hills, and the Downs are examples. In all these cases the dip of the strata is moderate. In highly eroded regions of steeply inclined strata the surface-features are sometimes regular, showing a succession of parallel mountain-ranges with intervening hollows. Sometimes, however, they are more or less irregular, the hills and mountains being grouped together without any trace of linear arrangement. The Highlands of Scotland to some extent illustrate the former class

of relict mountains, the general trend of the ranges and intervening depressions of certain areas being S.W. and N.E. In the Southern Uplands the same linear arrangement is occasionally apparent, but hardly so marked as in some parts of the Highlands. The difference is probably in chief measure due to the fact that throughout the Southern Uplands the rocks show little variety, while in the Highlands the reverse is the case, zones and belts of very different kinds of rock alternating.

The forms assumed by the relict mountains of a highly denuded plateau of erosion do not necessarily differ from those of similarly constructed tectonic mountains. The folded mountains of a region of uplift, after long-continued denudation, eventually become greatly modified, the dominant elevations no longer coinciding with anticlinal axes, but with the outcrops of the more resisting rock-masses, and now and again with synclinal axes. Such highly modified tectonic mountains, from a certain point of view, might be described as mountains of circumdenudation, but it is better to distinguish them. They should be recognised as tectonic mountains through all the various stages of erosion, until they are reduced to their base-level. Should such a plain of erosion become a plateau, the mountains eventually carved out of it might well repeat the forms and the arrangements of the antecedent tectonic mountains, but they would be true relict mountains—the dominant portions of a highly degraded plateau.

4. *Valleys.* The term valley has various significations. Usually we mean by it the hollow through which a stream or river flows. But some valleys contain no streams; they are mere elongated depressions—either narrow or broad, shallow or deep. Naturally, however, all depressions in the surface of a land which is not rainless tend to be filled or traversed by running water. By far the great majority of valleys—using the word in its widest meaning—are either the direct result of erosion, or have been greatly modified by it. Nevertheless, not a few valleys owe their origin to other causes. In short, we can recognise at least two kinds of valleys, viz., (*a*) valleys which have been formed either by hypogene action or by epigene action other than that of running water; and (*b*) valleys which are true hollows of erosion. These we shall briefly describe as *original* or *tectonic valleys*, and *subsequent* or *erosion valleys.*

(*a*) *Original or Tectonic Valleys.* Of these we distinguish two kinds—valleys which owe their origin to the irregular accumulation or heaping up of materials at the surface, and valleys which are the result of crustal deformation. The former class, or *constructional valleys* as they may be termed, are of comparatively little importance. They occur sometimes in volcanic regions as depressions in the surface of the various volcanic accumulations, or as hollows separating adjacent cones, sheets of lava, or heaps of ejecta. Similarly the depression lying between lines and ranges of dunes and moraines may be termed

constructional valleys. Sometimes such valleys trend for miles in one and the same direction ; more usually, perhaps, they are winding, short, and interrupted. In a word, any hollows at the surface produced by the irregular distribution of materials, whether by volcanic action or by epigene action of any kind, we should class as *constructional valleys.*

Of much more importance are *deformation-valleys.* Theoretically we may group these as (1) *dislocation-valleys* and (2) *synclinal valleys.* But not infrequently a deformation-valley has been determined partly by fracture and partly by flexure, such as the valley of the Jordan. Dislocation-valleys may extend for long distances between parallel faults, or they may follow the line of one great dislocation alone. Valleys of this kind are approximately straight or gently curved, and are of not infrequent occurrence. The valley of Glen App in Ayrshire and the great hollow traversed by the Caledonian Canal are good examples. The valley of the Rhine between the Vosges and the Black Forest is another. Synclinal valleys, as might have been expected, are best developed in mountains of recent uplift, where the surface-features not infrequently coincide more or less closely with the underground rock-structure. Such valleys naturally trend in the same general direction as the mountains amongst which they occur.

Original or tectonic valleys of all kinds are, of course, liable to modification by erosion. Many constructional valleys, it is true, are dry, and in the

absence of running water may remain for long periods comparatively unchanged. But wherever rain falls and water flows we look for evidence of erosion. Hence, even the most recently formed dislocation and synclinal valleys show traces of modification. As regards the older dislocation-valleys, so great has been the amount of subsequent erosion that the valleys as we now see them have obviously been excavated by epigene action. They are simply hollows which have been worked out along lines of weakness. As such dislocations go down to great but unknown depths, they necessarily affect a vast thickness of rock. However much, therefore, these rocks may be denuded, the fracture remains as a line of weakness, and determines the direction of erosion. The surface may have been planed down again and again to a base-level, but with each re-elevation a valley tends to reappear in the same place. Synclinal valleys, on the other hand, are far less persistent. When we find a river flowing continuously along the bottom of a synclinal hollow, we may usually feel assured that the hollow is of relatively recent geological age. To this, however, there are occasional exceptions.

(*b*) *Subsequent or Erosion Valleys.* If it be sometimes hard or even impossible to draw a clear line between original and relict mountains, it is just as difficult to separate tectonic from subsequent valleys. No doubt it is easy enough to distinguish between a young anticlinal mountain and any relict mountain carved out of a plateau. But even the

youngest deformation-mountains have sometimes been so denuded that they might be classed as relict mountains. It is the same with valleys. Dislocation-valleys no doubt tend to endure; they occupy more or less permanent lines of weakness. Synclinal valleys, on the other hand, soon become modified. The mountains on either side are weakly built, and are thus prone to collapse, while the intervening synclinal structure offers stronger resistance. The rivers no doubt flow at first along structural hollows or synclinal troughs, but in time the lines of drainage tend to become modified; a river shifts its course as the anticlinal mountains are reduced, and the syncline ere long ceases to form a valley. It is not surprising, therefore, to find that the strike-valleys of a recent mountain-uplift often do not coincide with synclinal troughs, but are true valleys of erosion. It is just in such regions, however, where tectonic valleys are of most frequent occurrence. We can have but little doubt that all the longitudinal rivers of a recent mountain-chain flowed at first in true structural or tectonic hollows. Possibly also the transverse valleys of such a chain may sometimes have been determined by minor folds and fractures. In the main, however, they are the result of erosion.

In ancient plateaux of erosion, composed of highly flexed and faulted strata, we not infrequently encounter surface-features which recall those of recent mountain-chains. Such plateaux often assume a mountainous aspect, and the mountains sometimes

exhibit a more or less well-marked series of long parallel ranges with intervening longitudinal depressions. Transverse valleys also can be recognised, but these present certain marked contrasts to the transverse valleys of a recent mountain-chain. The latter are generally arranged at approximately right angles to the longitudinal valleys, and are consequently, upon the whole, of less importance than these.[1] In a denuded plateau of erosion, however, the transverse valleys radiate in different directions from the more elevated portions of the plateau, cutting persistently across the parallel ranges and longitudinal depressions at all angles, and forming the highways of the more important rivers. It is only occasionally that the larger rivers flow in the direction of the strike. In short, it becomes obvious that the trend of the larger rivers in an ancient plateau of erosion has been determined by the original slopes of the surface, and has only an accidental connection with particular geological structures. In the gradual development of mountain and valley, however, the varying resistance offered by the different kinds of rocks and rock-arrangements has naturally come into play. Hence we find mountain-ranges tend to be developed along

[1] This, however, is only true in a general way, and is most conspicuously the case when a mountain-chain is relatively broad. In the Alps, for example, most of the larger and longer valleys are longitudinal. In mountain-chains of inconsiderable width the longitudinal valleys are less broad and more frequently interrupted, and the transverse valleys become relatively more important. Frequently, indeed, the rivers flowing from the dominant crests of such chains follow at first a somewhat zigzag course—now running in longitudinal hollows, now crossing the strike—until eventually they become wholly transverse.

the outcrops of the harder or more durable rocks. And thus it is obvious that the intervening parallel depressions or longitudinal valleys must as a rule be of later origin than the main lines of drainage which traverse the strike at all angles. In short, when the surface-features of such a denuded plateau are compared with the aspect presented by the folded mountains of a recently elevated chain, we find that the contrasts are much more striking than the resemblances. In the former the main lines of drainage are independent of the geological structure, the larger and more prominent valleys radiating in many different directions, and thus traversing the strike at all angles. If they sometimes follow the strike it is only when that has happened to coincide in direction with the slope of the ancient plateau. In general, however, the strike-valleys of such a region have been worked out by lateral streams. In the case of a broad mountain-chain of recent uplift, on the other hand, the main lines of drainage—the longer and broader valleys—follow the strike, while the narrower and shorter transverse valleys open into these primarily at approximately right angles. In time, however, many modifications necessarily occur, and the same streams and rivers are found flowing now in one direction, and now in another, sometimes following, and at other times crossing, the strike. In a word, the valleys that traverse an old plateau are wholly the work of erosion, the direction of the principal drainage-lines having been determined by the

surface-slopes of the original plane of denudation, and not by the geological structure. The principal valleys of a young mountain-chain, on the other hand, coincided at first with great structural hollows; and not a few still follow the lines of synclinal troughs and longitudinal fractures and dislocations.

If it be true that the valleys of a plateau are the work of erosion, this is not less true of the river-valleys of lowland regions. The main direction of the drainage in such regions has doubtless been determined by the average slope of the original surface, and has no necessary connection with the geological structure of the underlying rocks. But however independent of the general rock-arrangement the average direction of the rivers may be, it is obvious that their courses have often been profoundly modified by the nature and structure of the materials through which these courses have been cut. Not only are they liable to frequent deflection, but the form and character of the valley constantly change as different kinds of rock and rock-structures are traversed. A river cutting through horizontal strata or igneous rocks with well-marked vertical jointing, is usually flanked by approximately vertical cliffs. But as the valley is widened the cliffs tend to become benched backwards or even to be replaced by slopes. So, again, courses cut in the direction of the dip, or against the dip, may be bounded on either side by steep cliffs, which, under the influence of epigene action, often become resolved into slopes as the val-

ley is widened. In all those cases the valley-cliffs and slopes on the one side have the same general aspect as those on the other. But when a river cuts its way along the strike of moderately inclined strata its course assumes a different form. On the one side cliffs, and on the other, where the rocks dip into the valley, slopes tend to be developed. Again, as a river in its journey across a wide tract will necessarily traverse rocks and rock-structures of very different degrees of durability, its valley will widen or contract according as the rocks are more or less readily eroded. In one place the river meanders through a plain bordered by gentle slopes, in another place it hurries through a narrow and sometimes approximately straight or gently winding gorge, the latter often indicating the site of former cascades, waterfalls, and rapids. In a word, every change in the form and character of a valley of erosion is determined by the nature of the rocks and rock-arrangements with which the river and its assistant agents have to deal.

Waterfalls frequently mark the outcrops of relatively hard rock-masses. The Falls of Niagara, for example, owe their origin to the intercalation of a bed of hard limestone amongst more yielding strata, which have a gentle dip upstream. By the constant wash of the water the soft shales underlying the limestone are gradually removed, and the overlying mass, losing its support, breaks away from time to time along its joint-planes. In this manner the Falls have slowly retreated from Queenstown, and the gorge of

Niagara has been formed. The Falls of Clyde are due to a precisely similar geological structure, and many ravines and gorges in the valleys of our lowlands have originated in the same way as the gorge of Niagara.

The occurrence of great waterfalls in a long-established hydrographic system is somewhat anomalous, and leads at once to the suspicion that the drainage-system has been interfered with. Waterfalls cannot be of any great age. Sooner or later they must be cut back and replaced by ravines or gorges. Their presence, therefore, shows either that the valleys in which they occur are throughout of recent age, and that the rivers have not yet had time to reduce such irregularities, or that the drainage-system, if long established, has since been disturbed by some other agent than running water. In deformation-mountains of recent age we naturally expect to meet with cascades and waterfalls, for the streams and rivers of such a region are relatively young. They have only, as it were, commenced the work of erosion. But plains and plateaux of erosion which have existed for ages as dry land, and in which a complete hydrographic system has been long established, should show no great waterfalls. Yet we find cascades and waterfalls more or less abundantly developed in all the plains and plateaux of Northern Europe and the corresponding latitudes of North America; and most of these lands are of very great antiquity, their main lines of drainage having been established for a long

time. Obviously the hydrographic systems have been disturbed, and the disturbing element has been glacial action. During the Ice Age the long-established preglacial contours were greatly modified. Frequently, indeed, the minor valleys in plateaux and plains were completely obliterated, while even the main valleys were often choked with *débris*. When glacial conditions passed away, and streams and rivers again flowed over the land, they could not always follow the old lines of drainage continuously, but were again and again compelled to leave those and to cut out new courses in whole or in part. Hence the frequent occurrence of cascades and waterfalls in formerly glaciated lands.

Another cause for the existence of waterfalls in long-established hydrographic systems must be sought for in crustal disturbances. In general, deformations of the crust would seem to have been very gradually brought about, so gradually, indeed, that they have often had little or no influence upon the courses of great rivers. Anticlines slowly developing across a river-valley have been sawn through by the river as fast as they arose. Dislocations, in like manner, would seem to have been very slowly developed. Frequently these have traversed a river-valley without in any way disturbing the drainage, the rate of erosion having been equal to that of the displacement. On the other hand, we know that faulting or dislocation may sometimes be rather suddenly effected. Thus, a large fault crossing a river-valley

and having its downthrow in the direction in which the river is flowing would certainly produce a waterfall. Such, indeed, would appear to be the origin of the great falls of the Zambesi.

A volume might be written on the many appearances presented by subsequent or erosion valleys, but it is beyond our purpose to enter into further details. It is enough to recognise the fact that the great majority of river-valleys have been excavated by the rivers themselves. Even the most recent tectonic valleys have often been profoundly modified by subsequent erosion. In all regions, whatever their character may be, whether plateaux and plains of erosion or accumulation, or true mountains of elevation, the streams and rivers are constantly striving to reduce the land to their base-level. The main directions or lines of erosion are early established; but in the course of time many modifications arise, owing to the work of the streams and rivers and of epigene agents generally. At first, it may be, the rivers descend by a succession of steps or by alternate steep and more gentle declivities. Cascades, waterfalls, and rapids, and here and there barrier-lakes, may abound. But eventually the irregularities are removed and a true curve of erosion is produced. Each river has then its relatively short torrent-track, and its longer valley- and plain-tracks. As erosion proceeds the plain-track continues to encroach inland upon the valley-track, while the latter eats back into the torrent-track. At the same time the entire surface of the land is being

continuously reduced, until at last hills and mountains gradually disappear, and the whole region is replaced by a plain. The cycle of erosion, however, is not often allowed to proceed without interruption. Sometimes an upward movement increases the gradients, and so in time the revived rivers deepen their courses, and "valley within valley" appears. Or the whole region may become subject to glaciation, during which the preglacial drainage-system may be considerably modified by erosion here and accumulation there. When at last the ice-covering vanishes, lakes, rapids, cascades, and waterfalls diversify the water-courses. But the removal of these features is only a matter of time. By and by all the direct effects of glaciation must disappear. Again, long before a cycle of aqueous erosion is completed the land may be submerged and more or less deeply covered under new accumulations. Should re-elevation eventually ensue, a new hydrographic system will then come into existence, but this may not coincide in any part with that of the old buried land-surface.

In regions where soluble rocks, such as limestone, abound, the hydrographic system usually presents strong contrasts to those we have just been considering. Much of the rainfall finds its way below ground, where a complex series of channels is gradually licked out, until eventually the whole drainage may become subterranean. Usually, however, the drainage is partly superficial and partly underground, the rivers flowing for longer or shorter distances in ordinary

valleys of erosion, until they suddenly plunge below. Sometimes they emerge from their subterranean courses again and again; at other times they never reappear at the surface, but discharge their waters on the sea-floor. Owing to the frequent collapse of tunnels and caverns, the surface of a calcareous region is apt to show many irregular depressions, and the superficial hydrographic system is necessarily very imperfectly developed.

5. *Basins.* The large and small depressions of the surface, like other superficial features, have been formed in various ways. Some are the result of hypogene action, others owe their origin to epigene action, while yet others are due to both. Not a few, for example, are hollows caused by deformation of the crust, and may be termed *tectonic* basins. Some, again, occupy the site of extinct volcanoes, or are due in one way or another to volcanic action; they are our *volcanic* basins. Depressions caused by the removal of soluble materials from below, as in limestone countries, may be called *dissolution* basins; while the terms *alluvial* and *æolian* may well be applied to all basins which are the result of fluviatile and æolian action respectively. Landslips, etc., by obstructing drainage form a series of *rock-fall* basins, while glacial action is responsible for a large class of basins, some of which are rock-basins, others barrier-basins, and yet others partake of the character of both. All these are termed *glacial* basins.

Unless they are very capacious and extensive,

basins soon become obliterated. Erosion and sedimentation are too active to permit of their prolonged duration. Exceptionally, however, tectonic basins may long outlive the land-surface upon which they first appeared. If the deformation of the crust to which they owe their origin be continued, erosion and sedimentation may be unable to obliterate them. Should the bed of a great lake subside at approximately the same rate as alluvial matter accumulates upon it, while at the same time the effluent river cannot succeed in draining the lake dry, it is obvious that the latter may endure for a very long time. Sediments reaching a thickness of many thousands of feet might come to be deposited in such a lake, although the water itself had never been more than a few hundred feet in depth. The lake would form the base-level for all the surrounding region, the surface of which, perhaps mountainous to begin with, would be gradually lowered, and might pass through a complete cycle of erosion before the lake ceased to exist. In a word, a great lake or inland sea may become the burial-place of the high grounds that surround it, for it bears the same relation to these as an ocean to a continent.

The great majority of lakes, however, do not occupy tectonic basins, and must sooner or later disappear. Even tectonic basins, the beds of which have ceased to subside, must eventually be obliterated. As a matter of fact, none of the existing lakes of the world can be shown to be of great geological

antiquity. All alike, large and small, are of recent age. As regards their geographical distribution, it is singular and suggestive that they appear most abundantly in glaciated lands, in mountains, plateaux, and lowlands alike. None of these can be shown to have existed before the Glacial Period, and, with few exceptions, all must be attributed to the direct and indirect action of flowing ice. The preglacial hydrographic systems have been disturbed mainly by glacial erosion and accumulation. Many of the larger basins, however, such as those of Lakes Ladoga and Onega in Europe, and Lakes Superior, Michigan, and others in North America, are probably to a large extent tectonic, and due to warping or deformation of the crust. Not a few of the smaller lakes, again, occupy hollows caused by the irregular accumulation of fluviatile sediments, or by the blocking of streams, etc., by rock-falls and landslips, while here and there they rest in depressions produced by the dissolution and removal of soluble materials. Outside of the glaciated areas comparatively few lakes of any kind exist, and the most important of these occupy tectonic and volcanic basins.

6. *Coast-Lines.* Two types of coast may be distinguished, namely, *regular* or *smooth*, and *irregular* or *indented*. The former may be high and steep or gently shelving, and when expressed upon a map show a softly undulating or sinuous course. The shape assumed by the coasts themselves is naturally determined by the nature of the rock-masses and

their geological structure, and the manner in which they succumb before the action of waves and breakers. The coastal configuration is likewise influenced in many places by accumulation, for the coast-line is not fixed, but continually oscillates, retreating in some places, advancing elsewhere. Irregular or indented coast-lines are typically represented by such regions as Norway. Here the continuity of the coast-line is repeatedly interrupted by long inlets, while a multitude of islands fringe the land. Obviously, the trend of such a coast-line is determined by the configuration of the land; the long inlets and fiords are merely the submerged lower reaches of mountain-valleys. All highly indented coasts, indeed, are evidence that the land is either sinking now or has recently sunk.

In general, it may be said that the average trend and configuration of the coast-lines of the globe are determined by the position of the continents in relation to the great oceanic depression. The former are nowhere co-extensive with what is known as the continental plateau, considerable areas of which are below the sea-level. When the coast-lines approach the margin of that plateau, they generally continue for long distances in one particular direction, are rarely much indented, and show few or no fringing islands. Conversely, when they recede from the edge of the plateau, their trend becomes irregular, following now one direction, now another, numerous inlets appear, and marginal islands usually abound. Indented or irregular coasts are not the result of

marine erosion. Fiords, rias, and other indentations are simply submerged valleys. The intricate coast-lines of North-west Europe, of Greece and other parts of the Mediterranean lands, of Alaska, and many other regions have been determined by antecedent subaërial erosion.

CHAPTER XVII

CONCLUSION

THE STUDY OF THE STRUCTURE AND FORMATION OF SURFACE-FEATURES PRACTICALLY INVOLVES THAT OF THE EVOLUTION OF THE LAND.

IN the preceding chapters we have been inquiring into the origin of surface-features, and have come to the general conclusion that these cannot be accounted for without some knowledge of geological structure. We have learned that the crust of the earth has experienced many changes—rocks have been tilted, compressed, folded, fractured, and displaced. In some places elevation, in other places depression, has taken place, or both kinds of movement have affected the same area at different times. The crust has further been disturbed in many regions by vast intrusions of molten matter; while frequently volcanic action has cumbered the surface with lava and fragmental ejecta. It might seem, therefore, as if the varied configuration of our lands—mountain and valley, height and hollow—might be largely if not exclusively due to subterranean action. But the study of geological structure has shown us that enorm-

ous masses of material have been removed from the land-surface, and that however much that surface may have been influenced by crustal disturbance, yet its varied features, as a rule, owe their origin directly to denudation. Great mountain-chains have, indeed, been upheaved from time to time, fractures and displacements have again and again taken place; but even the youngest mountains have been so modified by the various epigene agents of change that frequently their original configuration has been almost completely destroyed. Earth sculpture, in a word, is everywhere conspicuous, and in regions which have remained for long ages undisturbed by subterranean action the latter has had only an indirect influence in determining the form of the surface. All the great ranges of tectonic mountains are of relatively recent age. Time has not yet sufficed for their complete reduction. On the other hand, the mountains that were upheaved in the earlier stages of the world's history have been either completely remodelled or entirely demolished. If elevations still often mark the sites of the chains and ranges of Palæozoic times, their internal geological structure yet shows that they are no longer tectonic but relict mountains. In short, we see that epigene agents are constantly endeavouring to remove the irregularities which result from crustal disturbance. Elevations are gradually lowered, and sunken areas filled up. But the process of levelling the land is not infrequently interrupted by renewed crustal movements.

No sooner, however, do fresh elevations appear than the cycle of erosion begins again.

> "The hills are shadows, and they flow
> From form to form, and nothing stands."

Although, as a rule, it is not hard to prove that certain surface-features owe their origin to erosion, it is often very difficult, or even impossible, to follow out the whole process—to trace the various stages in the evolution of surface-features. Pyramidal mountains composed of horizontally arranged beds are obviously relict mountains; they have been carved out of horizontal strata. That much anyone can see, and for the student of physical geography it is enough, perhaps, to be able to distinguish such mountains from those of a different build. But a geologist cannot be content with this: he will endeavour to trace out the whole history of the process. He will ascertain, if he can, the age of the strata, and the conditions under which they were accumulated, and subsequently elevated and eroded. It is the story of the evolution or development of the land and its surface-features that he will strive to unfold. In some cases the evidence is so simple, full, and clear, that its meaning can hardly escape him. More frequently, however, it is complicated, incomplete, and hard to read. We may have no doubt whatever that the various surface-features of the region we are examining owe their origin to denudation; but we shall often experience great difficulty in discovering the successive stages through which the land must have

passed before it assumed its present configuration. In this volume we have confined attention very much to the simple part of the subject, and have tried to show what kinds of features are due to hypogene and epigene action respectively. Incidentally, however, reference has been made to the successive geological changes which have preceded and led up to existing conditions. It is almost impossible, indeed, to consider the formation of surface-features without at the same time inquiring into their geological history. And not infrequently we find that the configuration of a land is the outcome of a highly involved series of changes. To understand the distribution of its hills and valleys, its plains and plateaux, and the whole adjustment of its hydrographic system, we may have to work our way back to a most remote geological period. But if it be true that the present cannot be understood without a knowledge of the past, it is no less true that physical conditions which have long passed away can often be realised in the existing arrangement of surface-features. This is no more than might have been expected; for if, as we all believe, there has been a continuity in geological history, the germ of the present must be found in the past, just as the past must be revealed in the present, if only we have skill to read the record. Evolution, in a word, is not less true of the land and its features than of the multitudinous tribes of plants and animals that clothe and people it.

This fascinating branch of geology has been fol-

lowed with much assiduity by many workers in many lands. But it is still in its infancy, and much remains to be accomplished. We have all learned the lesson of denudation. We know that rivers have excavated valleys, that the whole land-surface is being gradually lowered by the activity of the epigene agents. But comparatively few have set themselves the task of working out in all its details the history or evolution of the varied configuration of particular areas. Yet who can look at the map of a well-watered region, a land of mountain and glen, of rolling lowlands and countless valleys, without a wish to trace out the development of its numberless heights and hollows? What a world of interest must often be concentrated in the history of a single river and its affluents! At what time and under what conditions did it first begin to flow? How was its course and those of its tributaries determined? Has the hydrographic system ever been disturbed? and if so, to what extent and in what manner has it been modified? These and many similar questions will come before the investigator, and in searching for answers he must often unfold a strange and almost romantic history.

Naturally investigation of the kind leads up to the larger inquiry—When and how has the land itself been developed? It is matter of common knowledge that the lands within a common area are of very different age. Some have only recently appeared; others are of vast antiquity. And the older ones can always be recognised by the extent to which earth-

sculpture has been carried on. It is obvious, therefore, that a knowledge of the features produced by erosion, apart from other geological evidence, must often help us to determine the relative antiquity of land-surfaces. We do not doubt that when the history of the hydrographic systems of the continents has been better worked out, when the evolution of surface-features has been more closely followed, our knowledge of land-development will acquire a precision to which it cannot at present lay claim. Geologists will then also be better prepared to attack and perhaps to solve the largest problem of all—the origin of our continental areas and oceanic basins. Not that we can expect or desire that students of nature should refrain from theorising and speculating in that direction until the fuller knowledge we desiderate has been acquired. Theory must often be in advance of the evidence. It may be that we are already in possession of the truth—that the continental plateau and the oceanic depression, as many maintain, are primeval wrinkles of the crust. At present, however, this view can only be considered probable, or, as some would say, possible—a brilliant suggestion which seems to explain much that is otherwise unintelligible.

Another question that will obtrude itself when we are investigating the origin of surface-features is that of time. Surely a very long period would be required for the completion of a cycle of erosion, for the upheaval of a great mountain-chain and its subse-

quent resolution to a plain of erosion, for the cutting up of a lofty plateau into hill and valley, and its final complete degradation. We find it difficult to conceive the lapse of time involved in the process, and the difficulty is increased when we remember that cycles of erosion have frequently been interrupted by long pauses, during which the regions involved have been submerged, and not only protected from denudation, but more or less deeply buried under new accumulations. Yes, assuredly, we must admit that many long ages have passed since the process of land-sculpture began. But physicists tell us that we can no longer draw unlimited drafts upon the Bank of Time. We have no immeasurable and countless æons to fall back upon. Moreover, various estimates of the rate at which denudation is now being carried on, based as these are on the amount of materials carried seawards by rivers, have demonstrated that the demand for unlimited time is not justified. Even under existing moderate climatic conditions our own land is being levelled at a rate that will ensure its ultimate degradation within a period not so infinitely remote as geologists formerly supposed. In short, the cumulative effect of small changes is much greater than was at first realised. Further, their study of the past has taught geologists that the climate of the world has changed from time to time. And if so, then the rate of denudation must likewise have varied. In our own temperate lands we see how slowly erosion is effected—our streams and rivers are but seldom clouded with much sediment. Even after the lapse

of many years their courses remain apparently unmodified. In less temperate lands, however, erosion often proceeds apace; watercourses are deepened and widened in an incredibly short time. During a tropical storm of rain as much erosion of soil and rock and transport of material are effected within a limited drainage-area as would tax a British river with all its tributaries to accomplish in a year or a number of years. Now these islands of ours have experienced many vicissitudes—tropical, subtropical, and arctic conditions have formerly obtained here—and we need not doubt, therefore, that the present rate of denudation has often been exceeded in the past. When streams and rivers began their work of erosion in the British area, it is probable that the climatic conditions were more favourable for that work than is now the case. In a word, although the work performed by geological agents of change has been the same in kind, it has necessarily varied in degree from time to time. The present rate of erosion in Britain, therefore, can be no infallible index to that of the past. But however rapidly denudation may have proceeded in former ages, the shaping out of our hills and valleys, even under the most favourable conditions, must have been a slow process. Nevertheless recent investigations leave little room for doubting that the time required for the evolution of all the multitudinous forms assumed by the land has been exaggerated. The tale told by our relict mountains and erosion valleys does not support the claim for unnumbered millions of years.

APPENDIX

TABLE OF GEOLOGICAL SYSTEMS, AND THEIR PRINCIPAL SUBDIVISIONS.

QUATERNARY OR POST-TERTIARY	**Recent.**	
	Pleistocene.	
TERTIARY OR CAINOZOIC . .	**Pliocene.**	
	Miocene.	
	Oligocene.	
	Eocene.	
SECONDARY OR MESOZOIC . .	**Cretaceous.**	
	Danian (not represented in England).	
	Senonian (Upper Chalk with Flints).	
	Turonian (Middle Chalk).	
	Cenomanian (Lower Chalk and Upper Greensand).	
	Albian (Gault).	
	Aptian.	(Lower Greensand and Wealden beds).
	Urgonian .	
	Neocomian	
	Jurassic.	
	Purbeckian .	White Jura or Malm of Germany.
	Portlandian.	
	Kimeridgian	
	Corallian .	
	Oxfordian .	
	Bathonian . . .	Brown Jura or Dogger of Germany.
	Bajocian (Inferior Oölite)	
	Toarcian (Upper Lias) . . .	Black Jura or Lias of Germany.
	Liasian (Middle and Lower Lias in part)	
	Sinemurian (Lower Lias in part)	
	Hettangian (Infra-Lias) . .	
	Triassic.	
	Rhætic.	
	Keuper.	
	Muschelkalk (not represented in England).	
	Bunter.	

PRIMARY OR PALÆOZOIC	**Permian.**	
	Zechstein (Magnesian Limestone and Marl Slate).	
	Rothliegendes (Red Sandstones, Conglomerates, and Breccias).	
	Carboniferous.	
	Coal Measures.	
	Millstone Grit.	
	Carboniferous Limestone Series.	
	Devonian and Old Red Sandstone.	
	Devonian: Upper. Middle. Lower.	Old Red Sandstone: Upper. Lower.
	Silurian.	
	Upper.	
	Lower.	
	Cambrian.	
	Upper.	
	Middle.	
	Lower.	
	Pre-Cambrian or Archæan.	

[NOTE.—The names of the subdivisions of the various systems given in this table are those generally accepted. Many, it will be seen, are of English origin; others are foreign. Beside some of the latter the English equivalents (which are still current) are placed within parenthesis. A few German equivalents are given because reference is made to them in the text.]

GLOSSARY

Abrasion: the operation of wearing away by aqueous or glacial action.

Acid igneous rocks: rocks which contain a large percentage of silica to a small percentage of bases.

Agglomerate: volcanic fragmental rock, consisting of large angular, subangular, and roughly rounded blocks, confusedly huddled together.

Alluvium: a deposit resulting from the action of rivers or of tidal currents.

Amygdaloidal (Gr. *amygdalon*, an almond; *eidos*, an appearance): applied to igneous rocks containing vesicular cavities which have become filled, or partially filled, with subsequently introduced minerals. The cavities are frequently almond-shaped; the mineral kernels are termed *amygdules*.

Anticline (Gr. *anti*, against; *klino*, I lean): a geological structure in which strata are inclined in opposite directions from a common axis; *i. e.*, in a roof-like form. When its axis is vertical, an anticline is *symmetrical;* in an *unsymmetricel* anticline the axis is inclined.

Archæan: synonymous with Pre-Cambrian. See Table of Geological Systems.

Arenaceous: applied to strata which are largely or wholly composed of sand.

Argillaceous: applied to rocks composed of clay, or in which a notable proportion of clay is present.

Ash, volcanic: the finest-grained materials ejected during volcanic eruptions.

Basalt: a dark, hemicrystalline, basic igneous rock.

Base-level of Erosion: that level to which all lands tend to be reduced by denudation. A land *base-levelled* is usually very slightly above the sea-level, and shows a gently undulating or approximately flat surface.

Basic igneous rocks: rocks which contain a large percentage of bases to a low percentage of silicic acid.

Beaches, raised: former sea-margins; sometimes appear as terraces of gravel, sand, etc., sometimes as shelves cut in solid rock; occur at all levels, from a few feet up to several hundred yards above the sea.

Biotite (*Biot*, French physicist) : a black or dark-green mica ; occurs as a constituent of many crystalline igneous and schistose rocks.

Bombs, volcanic : clots of molten lava shot into the air from a volcano ; having a rotatory motion, they acquire circular or elliptical forms, and are often vesicular internally, or hollow.

Bosses : large amorphous masses of crystalline igneous rock which have cooled and consolidated at some depth from the surface, and are now exposed by denudation.

Boulder-clay : typically, an unstratified clay more or less abundantly charged with angular and subangular stones of all shapes and sizes up to large blocks ; the bottom or ground-moraine of prehistoric glaciers and ice-sheets.

Bunter (Ger. *bunt*, variegated) : one of the subdivisions of the Triassic system ; the sandstones of the Bunter are often spotted or mottled.

Buttes (Fr.) and **mesas** (Sp.) : names given, in the Territories of the United States, to conspicuous and more or less isolated hills and mountains. *Buttes* are usually craggy, precipitous, and irregular in outline ; *mesas* are flat-topped or tabular.

Cainozoic (Gr. *kainos*, recent ; *zoe*, life). See Table of Geological Systems.

Calciferous : applied to strata which contain carbonate of lime as a binding or cementing material ; or to strata among which numerous beds of limestone, or other calcareous rocks, occur.

Calc-sinter (Ger. *kalk* (calx), lime ; *sinter*, a stalactite) : a deposit from water holding carbonate of lime in solution.

Cambrian (Cambria or Wales) : name given by Professor Sedgwick to one of the Palæozoic systems which was first carefully studied in Wales.

Carboniferous : name given to the great *coal-bearing* system of the Palæozoic rocks.

Chalybeate (L. *chalybs*, steel) : applied to water impregnated with oxide of iron.

Chlorite (L. *chloritis*) : a greenish mineral present in some schistose rocks ; often occurs in igneous rocks as a product of alteration.

Clastic (Gr. *klastos*, broken): applied to rocks composed of fragmental materials.

Clinkers (Dut. *klinker*, that which sounds) : the cindery-like masses forming the crust of some kinds of lava.

Concretion : a body formed by irregular aggregation or accretion of mineral matter, very often round a nucleus ; may be spherical, elliptical, or quite irregular and amorphous. *Concretionary*, formed of or containing concretions.

Coulée (F.) : a stream of lava, whether flowing or become solid.

Crag-and-tail: a hill or crag showing an abrupt and often precipitous face on one side, and sloping away gradually to the low ground in the opposite direction.

Cretaceous: name given to the great chalk-bearing system of the Mesozoic strata.

Crust of the Earth: the outer portion of the earth which is accessible to geological investigation.

Curve of Erosion: A typical river has its steep mountain-track, its moderate valley-track, and its gentle plain-track. In the case of young rivers, the change from the one track to the other is often abrupt. In older river-courses, such irregularities tend to be more and more reduced—the transition from the one track to the other becomes gradual—until eventually the course may be represented by a single curve, flattening out as it descends from source to mouth. This is the curve of erosion.

Débâcle (F.): a tumultuous rush of water, sweeping forward rock *débris*, etc.

Deflation: the denuding and transporting action of the wind.

Degradation: the wasting or wearing down of the land by epigene agents.

Denudation: the laying bare of underlying rocks by the removal of superficial matter; the process by which the earth's surface is broken up and the materials carried away.

Derivative rocks: rocks which have been formed out of the materials of pre-existing minerals, rocks, and organic remains.

Detritus: any accumulation of materials formed by the breaking-up and wearing-away of minerals and rocks.

Devonian: name given to one of the Palæozoic systems; it is well developed in Devonshire.

Diluvium: name given to all coarse superficial accumulations which were formerly supposed to have resulted from a general deluge; now employed as a general term for all the glacial and fluvio-glacial deposits of the Ice Age.

Diorite (Gr. *dioros*, a boundary between): a crystalline igneous rock, belonging to a group intermediate in composition between the basic and acid groups.

Dogger: one of the subdivisions of the Jurassic system in Germany, etc.

Dolerite (Gr. *doleros*, deceptive): a crystalline basic igneous rock.

Dolina (It.): name given to the funnel-shaped cavities which communicate with the underground drainage-system in limestone regions. Similar cavities are known in this country as *sinks* and *swallow-holes*.

Dolomite (*Dolomieu*, the French geologist): carbonate of calcium and magnesium; occurs as a crystallised mineral, and also as a granular crystalline rock (magnesian limestone).

Drum, Drumlin (Ir. and Gael. *druman*, the back, a ridge): a ridge or bank of boulder-clay alone, or of "rock" and boulder-clay. Ridges of this kind often occur numerously. There seem to be two varieties—(*a*) long parallel ridges or banks, and (*b*) short lenticular hillocks; the former usually consist of glacial accumulations alone; the latter not infrequently contain a core or nucleus of solid rock, or they may show solid rock at one end and glacial materials at the other.

Dyas (LL. the number two): name sometimes applied to the Permian system with reference to its subdivision into two principal groups.

Eocene (Gr. *eos*, dawn; *kainos*, recent): see Table of Geological Systems.

Epigene (Gr. *epi*, upon; *gennao*, I produce): applied to the action of all the geological agents of change operating at or upon the earth's surface; also to all accumulations formed by the action of those agents.

Erratics: boulders and fragments of rock which have been transported, generally by the agency of glaciers or floating ice, and are therefore foreign to the places in which they occur.

Eruptive rocks: massive igneous rocks generally; properly only those which have been *extruded* at the surface are truly *eruptive*; molten masses which have been *intruded* in the crust, and therefore below the surface, are *irruptive*.

Eskers (Ir. *eiscir*, a ridge): ridges of gravel and sand which appear to have been formed in tunnels underneath the great glaciers and ice-sheets of former times; same as the Swedish *osar*.

Felspars (Ger. *feld*, a field; *spath*, spar): a group of minerals, common constituents of many igneous and schistose rocks.

Fire-clay: properly a clay suitable for the manufacture of fire-bricks; in geology, is applied to the argillaceous layer underlying most coal-seams, which consists generally of some kind of clay, but is not always suitable for fire-bricks.

Fluvio-glacial: applied to sedimentary deposits resulting from the action of streams and rivers escaping from a glacier or an ice-sheet.

Foliated rocks: another name for schist and schistose rocks. See **Schist**.

Formation: a series of rocks having some character in common, whether of origin, age, or composition; often applied to a group of strata containing a

well-marked and distinctive assemblage of fossils—a group of subordinate importance to a *system*.

Fragmental rocks: see **Clastic** and **Derivative.**

Gabbro (It.): a coarsely crystalline basic igneous rock.

Geanticline (Gr. *ge*, the earth; and F. *anticline*): a broad or regional arching or bending up of the crust—thus, a geanticline may be composed of strata showing all kinds of geological structure. It is simply a bulging or swelling up of the crust which affects a wide region. *Geosyncline* is just the opposite: it is a wide or broad region of depression, *i. e.*, a sinking of the earth's crust as a whole.

Geysers (Icel.): eruptive fountains of hot water and steam.

Giants' kettles: large pot-holes often observed in the deserted beds of old glaciers; they are believed to have been drilled by water descending from the surface of the glaciers and setting stones and boulders in rapid rotation.

Glacial Period: the deposits of the Ice Age referred to in the text belong for the most part to the Pleistocene system. Cold climatic conditions, however, had set in before the close of the Pliocene, and were continued into the Recent period—the last of our snow-fields and glaciers having vanished during the formation of some of the youngest raised beaches—a time when Neolithic man lived in Britain.

Gneiss (Ger.): one of the more coarsely crystalline schistose rocks.

Granite (It. *granito*): one of the deep-seated plutonic crystalline igneous rocks. *Granitoid*, having the structure of granite.

Greywacke (Ger. *grauwacké*): a sedimentary rock, somewhat metamorphosed; common in the Palæozoic systems.

Grit: generally a coarse-grained arenaceous rock; the harder kinds are used for grindstones.

Ground-moraine: the rock-rubbish formed by the grinding action of glaciers and ice-sheets.

Gypsum (Gr. *gypsos*, chalk): a crystalline mineral composed of sulphate of lime.

Hade: a miner's term for the inclination or deviation of a lode or fault from the vertical.

Hæmatite (Gr. *haimatites*, blood-like): a mineral compound of oxide of iron, which yields a blood-red streak when scratched.

Holocrystalline (Gr. *holos*, whole; F. *crystalline*): applied to igneous rocks composed entirely of crystalline ingredients, as granite.

Hornblende (Ger. *horn*, horn ; *blenden*, to dazzle) : a mineral constituent of many crystalline igneous and schistose rocks.

Horste : name given by German geologists to isolated mountains severed by dislocations from rock-masses with which they were formerly continuous, but which have since subsided to a lower level. *Rumpfgebirge* (*lit.*, rump-mountains) is another name for this type of mountain.

Humous acids : general name for the various acids met with in the humus or vegetable mould, and which are derived from the decomposition of organic matter.

Hypogene (Gr. *hypo*, under ; *gennao*, I produce) : applied to geological action under the earth's surface, and to the products of that action ; opposed to **Epigene** (*q. v.*).

Infraglacial : applied to deposits formed and accumulated underneath, or in the bottom parts of, glaciers and ice-sheets ; and to the geological action of the ice upon rocks over which it flows.

In situ : in its original situation ; applied to minerals, fossils, and rocks which occupy their natural place or position.

Insolation : the geological action of the sun's heat upon rocks at the surface.

Intraglacial : applied to rock-fragments embedded in the central and upper portions of glaciers and ice-sheets.

Intrusive rocks : molten rocks which have been injected among pre-existing rock-masses.

Inversion : a geological structure in which strata have been so folded as to be turned upside down.

Isoclinal (Gr. *isos*, equal ; *klino*, to lean) : applied to strata folded in a series of unsymmetrical anticlines and synclines whose axes all incline in one and the same direction.

Joints : natural division-planes which intersect bedded and amorphous rocks of all kinds. In bedded rocks two sets of joints are usually recognisable (*master-joints*), which cut each other at approximately right angles. In crystalline igneous and schistose rocks the joints as a rule are somewhat irregular ; but to this there are exceptions—as in certain granites, basalts, etc.—many of the fine-grained igneous rocks showing prismatic jointing or columnar structure.

Jurassic (from *Jura* Mountains) : one of the Mesozoic systems.

Kames : ridges and mounds of gravel and sand generally, but now and again of rude rock-rubbish. They are of glacial and fluvio-glacial origin, having been accumulated, in many cases, along the terminal margins of large glaciers and ice-sheets.

Kaolin (Chin. *kaoling*): a fine clay resulting from the chemical decomposition of felspar.

Keuper (Ger.): one of the subdivisions of the Triassic system.

Laccolith (Gr. *lakkos*, a cistern; *lithos*, stone): name given to intrusive rocks which, when rising from below, have spread out laterally, so as to form lenticular masses, thereby lifting the rocks above them so as to form dome-shaped swellings at the surface.

Lapilli (L.): small stones ejected from volcanoes in eruption.

Lee-seite (Ger.): the side of a hill or prominent rock in a glaciated region which has been sheltered or protected by its position from the abrading action of the ice-flow. The opposite side, exposed to that action, and therefore "glaciated," is termed the *Stoss-seite*.

Lias: one of the subdivisions of the Jurassic system.

Lignite: brown coal, not so highly mineralised as common coal.

Maars: name given in the Eifel to crater-lakes.

Macalubas: mud-volcanoes, so called from the well-known Macalube, near Girgenti, in Sicily.

Magma: the molten or plastic material which, when cooled and solidified, forms crystalline, hemicrystalline, or glassy igneous rocks.

Malm: one of the subdivisions of the Jurassic system in Germany, etc.

Master-joint: see **Joints**.

Mesa: see **Buttes**.

Mesozoic (Gr. *mesos*, middle; *zoe*, life): see Table of Geological Systems.

Metamorphic (Gr. *meta*, expressing change; *morphe*, form): applied to rocks which have been more or less completely changed in form and structure—their constituent materials having been rearranged.

Mica: a group of minerals, common constituents of many igneous and schistose rocks.

Millstone Grit: one of the subdivisions of the Carboniferous system.

Miocene (Gr. *meion*, less; *kainos*, recent): one of the Cainozoic systems.

Monocline (Gr. *monos*, single; *klino*, to lean): the simplest kind of fold; an abrupt increase of dip in gently inclined or approximately horizontal strata, followed by an equally abrupt return to the original position.

Moulin (F., a mill): an approximately vertical cavity or shaft worked out in a glacier by water descending from the surface through a crevasse. See **Giants' kettles**.

Necks: plugged-up pipes of volcanic eruption; the throats of old volcanoes which have been laid bare by denudation.

Névé (F.): granular snow; the condition assumed by snow on its passage into glacier-ice.

Obsidian: a volcanic glassy rock.

Old Red Sandstone: see Table of Geological Systems.

Oligocene (Gr. *oligos*, little; *kainos*, recent): one of the Cainozoic systems.

Olivine: a greenish mineral; a common constituent of many basic igneous rocks.

Oölite (Gr. *oön*, an egg; *lithos*, stone): a granular limestone, common in the Jurassic system, which on this account used to be known as the Oölitic formation.

Osar (Swedish): see **Eskers**.

Outlier: a detached mass of rock resting upon and surrounded on all sides by older rocks.

Overfold: an overturned or inverted fold; the axis so inclined that one limb of the fold is doubled back under the other. When the axis becomes horizontal, or nearly so, the fold is *recumbent*.

Overthrust: a faulted overfold; the fold has been dislocated, and one limb pushed over the other along a thrust-plane.

Palæozoic (Gr. *palaios*, ancient; *zoe*, life): see Table of Geological Systems.

Parallel roads: old lake-beaches, seen in Glen Roy (Scottish Highlands) and other valleys in its neighbourhood.

Paysage morainique: a region abundantly covered with terminal moraines.

Perched blocks: boulders transported by glacier-ice and stranded in prominent positions.

Petrography (Gr. *petros*, a rock; *grapho*, to describe): the study of rocks—Petrology and Lithology.

Phonolite (Clinkstone) (Gr. *phone*, sound; *lithos*, stone): a volcanic crystalline rock; when fresh and compact it has a metallic ring or clink under the hammer.

Pleistocene (Gr. *pleistos*, most; *kainos*, recent): one of the Post-Tertiary systems.

Pliocene (Gr. *pleion*, more; *kainos*, recent): one of the Cainozoic systems.

Plutonic (Pluto, the god of the infernal regions): applied to deep-seated igneous action; also to deep-seated igneous rocks — those which have cooled and consolidated at some depth from the surface.

Post-Tertiary or **Quaternary**: the youngest group of systems. See Table.

Pre-Cambrian or **Archæan**: the oldest system of rocks.

Pumice: any froth-like, foam-like, spongy, porous, or cellular lava.

Pyroxene (Gr. *pur*, fire; *xenos*, a guest): a family of minerals, common constituents of many crystalline igneous, and of some schistose rocks.

Quadersandstein: name given in Saxony, Bohemia, and Silesia to the Cretaceous system; so called because the sandstone of which it is chiefly composed is traversed by abundant well-marked vertical joints, that cause the rock to weather into *square*, tabular, and pyramidal hills, and pillar-like masses.

Quaquaversal (L. *quaqua*, wheresoever; *versus*, turned): applied to strata which dip outwards in all directions from a common centre; dome-shaped strata.

Quartz (Ger.): common form of native silica; the most common of all rock-forming minerals.

Quaternary: alternative name for Post-Tertiary.

Raised beaches: see **Beaches**.

Recent period: the latest of the geological systems; passes gradually into the present or existing condition of the earth.

Reversed faults: in these the hade or inclination of the fault is in the direction of upthrow—lower rocks having been pushed over higher rocks. See **Overthrust** and **Thrust-plane**.

Revived rivers: when the rivers of a region have succeeded in cutting their channels down to the base-level, they have a slight fall and flow sluggishly. Should the whole region then be elevated, while the direction of its slopes remains unchanged, the erosive energy of the rivers is renewed, and they are said, therefore, to be *revived*.

Rhætic (from the Rhætian Alps): one of the subdivisions of the Triassic system.

Rhyolite (Gr. *rheo*, to flow; *lithos*, stone): an acid volcanic rock.

Roches moutonnées: rocks rounded like the back of a sheep; name given to rocks which have been abraded, rounded, and smoothed by glacial action.

Rothliegendes (Ger.): one of the subdivisions of the Permian system.

Rumpfgebirge (Ger.): same as **Horste** (*q. v.*).

Salses (Fr.): another name for *mud-volcanoes* or **Macalubas** (*q. v.*).

Schist (Gr. *schistos*, easily split): a crystalline rock in which the constituent minerals are arranged in rudely alternate parallel layers or folia; a foliated rock.

Scoriæ (Gr. *skoria*, dross): loose fragments of slaggy, cindery lava.

Screes (Icel. *skritha*, fallen rocks on a hillside): a Westmoreland term for the sheets of loose angular stones which gather upon hillsides and at the base of cliffs, etc.

Shearing: the yielding of a rock to compression, strain, and tension during crustal movements, whereby the solid mass is compelled to flow, so that a kind of fluxion-structure is developed in it; frequently under such conditions dislocation takes place—the rock gives way and one mass is pushed over another.

Sheet: molten matter intruded between bedded rocks.

Stalactites (Gr. *stalaktos*, dropping): the icicle-like pendants hanging from the roofs of limestone caves, formed by the drip of water holding carbonate of lime in solution.

Stalagmites (Gr. *stalagmos*, a dropping): the calcareous deposit formed upon the floor of a cavern by the drip of water from the roof.

Stoss-seite: see **Lee-seite**.

Striæ, glacial: scratches, furrows, etc., engraved upon rock-surfaces by glacial action.

Strike: the general direction or run of the outcrops of strata.

Swallow-holes: see **Dolina**.

Syenite (from Syene, Egypt): a holocrystalline igneous rock of deep-seated origin.

Syncline (Gr. *syn*, together; *klino*, I lean): a basin or trough-shaped arrangement of strata; the strata dip from opposite directions inwards to one common axis. When the axis is vertical the syncline is *symmetrical*; when inclined, *unsymmetrical*.

Systems: the larger divisions of strata included under the Palæozoic, Mesozoic, Cainozoic, and Quaternary groups.

Terrigenous: applied to marine accumulations the materials of which have been derived from land; opposed to *abysmal*, applied to marine deposits the constituents of which have not been so derived.

Thrust-plane: a **Reversed fault** (*q. v.*), the hade or inclination of which approaches horizontality; a common structure in regions of highly flexed rocks.

Till: another name (Scottish) for **Boulder-clay** (*q. v.*).

Tors: the peculiar and often fantastic prominences met with in regions of granite which have been long exposed to weathering, as on Dartmoor. The *kopjes* of Mashonaland are an example of the same phenomenon.

Trachyte (Gr. *trachys*, rough): a hemicrystalline volcanic rock.

Travertine: another name for **Calc-sinter** (*q. v.*).

Triassic (Gr. *trias*, three): one of the Mesozoic systems.

Tufa, or **calcareous tufa:** same as **Calc-sinter, Travertine** (*q. v.*).

Tuff: a volcanic fragmental rock; usually applied to the finer-grained ejecta of volcanic eruptions; may consist almost entirely of *lapilli* (*q. v.*) or of the finest sand and dust, or of a mixture of coarse and fine ingredients.

Unconformable: not conforming in position, or not having the same inclination or dip with underlying rocks; applied to strata which rest upon an eroded surface of older rocks; *unconformity* or *unconformability*, the condition of not being conformable.

Underclay: the bed upon which a coal-seam rests.

Uniclinal (L. *unus*, one; Gr. *klino*, to lean): applied to a series of strata dipping in one and the same direction.

Upthrow, upcast: that side of a fault on which the strata lie at a higher level than their continuations on the other side of the fault. Normal faults are usually described as *downthrows;* reversed faults as *upthrows*.

Wâdy (Ar.): a ravine or watercourse, dry except in the rainy season. Some wâdies are perennially dry.

Weathering: applied to the decomposition, disintegration, and breaking up of the superficial parts of rocks under the general action of changes of temperature, and of wind, rain, frost, etc.

Zeolites (Gr. *zeo*, I boil; *lithos*, stone): a group of minerals, so called because they bubble up in the blowpipe flame; often met with filling up vesicular cavities, etc., in igneous rocks.

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